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UPON THE MAGNETIC SEPARATION OF THE LINES OF BARIUM, YTTRIUM, ZIRCONIUM, AND OSMIUM

By B. E. MOORE

I. INTRODUCTION

The investigations of Balmer,[1] followed by Rydberg[2] and by Kayser and Runge,[3] showed that many of the spectral lines of different substances formed series, which could be expressed by a simple empirical equation. Preston,[4] in the study of the Zeeman effect, observed that similar series for different substances had identical magnetic separation of the lines, when these separations were measured in wave frequencies instead of wave-lengths. Preston's data were very meager and his law was first thoroughly established by Runge and Paschen.[5] Inversely then lines of like magnetic separation are members of a series, according to Preston's law, and therefore

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[1] *Wied. Ann.*, **25**, 80, 1885.

[2] *Phil. Mag.*, (5), **29**, 331, 1890; *Zeit. Phys. Chem.*, **5**, 227, 1890; *C. R.*, **110**, 394, 1890; *Kgl. Svenska Vet. Akad. Handl.*, **32**, Nr. 11, 1890; *Astrophysical Journal*, **6**, 239 and 338, 1897.

[3] C. Runge, *Report Brit. Assoc.*, 1888, pp. 576, 577; Kayser and Runge, *Wied. Ann.*, **41**, 302, 1890; **43**, 385, 1891; **48**, 126, 1893; **52**, 93, 1894; Runge and Paschen, *Berl. Ber.*, 1895, 639, 759; *Astrophysical Journal*, **3**, 4, 1896; *Wied. Ann.*, **61**, 641, 1897; *Astrophysical Journal*, **8**, 70, 1898.

[4] *Phil. Mag.*, (5), **45**, 325, 1898; *Proc. Royal Dub. Soc.*, **6**, 385, 1898; *ibid.*, **7**, Part II, p. 2.

[5] *Sitzungsber. der Berl. Akad.* am 6. Feb., 1902; *ibid.*, **19**, 380, 720, 1902; *ibid.* (Runge and Precht), **10**, 417, 1904; *Astrophysical Journal*, **15**, 235, 333, 1902; *ibid.*, **16**, 123, 1902.

the magnetic separation may be used to establish series. In fact, Runge suggested this possibility, and applied it to barium where no series had been discovered. He found that barium gave representatives of series, but not in sufficient number to establish the series.

The following experiments propose to use this inverse method, first in a more complete study of barium, and then in other substances wherein no series have been found, to see whether a series relationship can be established in any of the different types of magnetic separation.

II. EXPERIMENTAL METHOD

The spectral lines were photographed by means of a 21-foot concave grating with a fixed circular camera. The light consisted of a spark of the substance which had been dried upon thin carbon plates and so placed in a strong magnetic field that the spark was parallel to the lines of force.[1] Owing to the varying intensity of the different lines photographs were taken with different lengths of exposure, varying from fifteen minutes to two hours in the violet up to six hours in the red. The photographs were all taken with the pole pieces at the same distance apart, so that by varying the current on the electromagnetic circuit one could obtain *ad libitum* any field-strength up to the maximum of 24,400 lines per sq. cm. The field-strength was determined by repeated measurements of the separation of the calcium line 3968.6, which occurs on account of an impurity in the carbon electrode, and by a few special photographs of the zinc line 4680, assuming Runge's measurements for these lines at 31,000 C. G. S. units to be correct. All calculations are given at the above maximum field-strength. Other field-strengths were used to determine the true components of lines very close together or to obtain readings for overlapping components. Frequently such lines are determined from the distance of the one free component from the undisturbed position. Photographs of vibrations parallel to the lines of force were taken upon one set of plates, and perpendicular to the lines of force upon another set of plates. This was effected in the usual way by means of a calcite prism. Photographs taken without the calcite, i. e., with both the parallel and perpendicular components on one set of plates,

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[1] Many substances adhere so well to carbon that the writer thinks this plan, together with the circular camera, will make it possible to photograph some of the promising costly substances.

were used only to obtain the relative intensity of the parallel and perpendicular components. In these photographs the parallel and perpendicular components often are so close to each other as to prohibit their separation, and thus preclude any knowledge of their respective intensities. In triplets of large separation, however, it was a matter of no difficulty. By a double comparison of such lines with corresponding components on parallel and perpendicular plates, the ratio of the intensities of the parallel and perpendicular plates is established. The lines may then be compared on perpendicular and parallel plates, although the conditions of exposure and development may have been quite different. But withal there is a chance for a very large error in intensities, since there is a wide range in width and depth of the shadows, and no experimental method is employed to compare the intensities of the shadows, as is done in photometry and spectro-photometry.

The variation in actinic sensibility of the plates throughout the spectrum is enormous, so that one must resort to differently prepared plates. Furthermore, the red sensitive plates, self-prepared with dicyanin, were far from uniform. Hence, a comparison of intensities of different lines, which is very important in investigation for series, can be roughly accurate only within a short spectral range. This is generally sufficient to show that two, or more, near lines of like magnetic separation, but of great inequality in intensity, do not belong to the same series. This is all that should be expected from the intensities given in the following experiments. How great the variations in intensities may be under the different conditions of experiment may be seen by comparing the intensities here recorded with those given in Exner and Haschek's tables, which have been freely used. There is enough similarity in intensities to make their tables serviceable for the identification of lines.

Intensities are recorded for the components of the first-order lines, whether the lines were measured in first or second order. The lowest intensity 1 is just observable. It is measurable only when very favorably located in a group of components and then with no special accuracy. A line of intensity 2 is capable of fair measurement in groups of several components, but is not satisfactory in a doublet of broad separation. Intensity 3 is the lowest intensity satisfactory under the latter conditions. Diffuse lines of higher intensities may also be unsatisfactory. A pair of components which are diffuse outward or inward indicates the presence of outer or inner weak components, which may be brought out when self-induction, capacity, slit-width, and exposure of plates have been properly balanced. Broad single lines suggest a similar possible resolution. Hence a record of these facts may be helpful, even if the resolution has not been effected. The accuracy of the readings also depends upon the sharpness of the lines. Where weakness, diffusion, or presence of overlapping components has made a reading less accurate, the result is tabulated in brackets. The bracketed values are still close enough to give a reasonable idea of the magnitude of the separation. Overlapping components can usually be circumvented by varying the field-strength. However, this did not always suffice, and it was necessary to omit an occasional component in a line, e. g., the outer violet component of zirconium 3573.3. There is large variation in definition among the lines of a substance. This is particularly noticeable in barium. The lines of osmium are uniformly exceptionally sharp, so that the readings in the latter possess nearly three times the accuracy of the former. Yttrium and zirconium occupy an intermediate position. The separations are determined from five readings for each component. These were all repeated and in most cases the repeated readings were upon other sets of plates. If the repeated readings showed an unwarranted deviation from the old result, the line was subjected to further analysis upon both plates. In zirconium there is certainly an error of 0.005 mm possible. Cases of double the magnitude may have escaped my attention but such cases are few. This value gives a minimum error in $\Delta\lambda/\lambda^2$ in the second order at 4500 of 0.025, and a maximum error in the first order at 3250 of 0.09. Hence it is desirable as far as possible to limit the readings in the shorter wave-lengths to the second order photographs.

The identification of the lines in the violet and ultra-violet spectra was made by the Exner-Haschek spark-spectrum tables, which generally proved very satisfactory. An occasional difficulty was met. For example, in zirconium a very well-defined line of eight components was found at about 4214 which failed to identify with impurities or with zirconium 4214.58. It does, however, identify with the arc light table line 4214.05. Such a difference in arc-line wave-length and spark-line wave-length is very exceptional, but in the absence of line 4214.58, it indicates that the line in question is the same. Rough measurements frequently gave readings closer to the arc-light lines than the spark lines, and many such might have been detected had very careful comparator measurements of distances from line to line been made. Sometimes such comparator measurements are necessary in identification as it may be a required line or impurity. Difficulty was encountered in three lines toward the red of 3392.20. These three lines measured from 3392.20 gave 3393.36 instead of 3393.30; 3394.96 instead of 3394.79, or possibly this is another line; and 3396.87 instead of 3396.71. A fourth line 3396.49 is certainly in close enough agreement with 3396.51. Several other lines appeared which have not been identified.

III. EXPLANATION OF TABLES

The abbreviations in the tables have the following significance, viz.: λ, wave-length; $\Delta\lambda/\lambda^2$, the change in vibration per cm; *s*, vibrations perpendicular to the lines of force, and *p*, parallel to the same; H, principal series; G, greater wave-length; K, smaller wave-length; N, subordinate series; S, satellite; *h*, principal line; R, observations according to Runge; M, observations according to Moore; *i*, intensity. Column A gives the approximate value of the components represented in terms of a small separation, called the "interval," multiplied by small numbers called "factors." The factors represent the ratio of the distances of the successive components from the position of the undisturbed line. Column B gives remarks. Inasmuch as duplicate remarks frequently occur, they have been designated by the following abbreviations, viz.: D, diffuse; D_r, diffuse toward the red; D_b, diffuse toward the blue; D_i and D_o, diffuse inward and outward respectively, which generally suggests the presence of interior and exterior weak components respectively; *w*, slightly broadened; *b*, much broadened; b_o and r_o, blue and red components respectively, overlapped by component of an adjacent or foreign line; n. i., not identified, i. e., the line does not compare with any line in Exner and Haschek's tables. Special remarks are indicated by numbers which are explained at the foot of their respective tables. In the quadruplet tables the *s*- and *p*-components are each designated by a double sign ($\mp$) to avoid repetition. The *s*-component is recorded first. The double sign therefore means two readings. The triplet *s*-components are similarly designated and the *p*-component is omitted. Two intensities are frequently given in the triplets. The first recorded value then represents the *s*-component and the second the *p*-component. When there are three intensities for triplets, the outer *s*-components are unequally intense. The first reading is then the red and the third the blue component. When only one intensity under triplets is given it refers to the *s*-component and the *p*-component has twice the intensity.

IV. BARIUM

The barium lines for wave-lengths shorter than 5854 were measured from plates exposed by Professor Runge. Much time was spent in trying to obtain stronger photographs of barium to bring out the weaker lines. These lines were either not upon the new plates or too diffuse for satisfactory measurements. A few of the sharpest lines of the new plates were measured and found in agreement with measurements made from Professor Runge's other lines. These observations and those by Professor Runge upon barium I have reduced to the field-strength, 24,400 C. G. S., used in all subsequent measurements. The photograph of the red spectrum yielded all lines but two in Kayser and Runge's arc spectrum, and several new lines, most of which are weak. The wave-lengths of these lines are determined from their distances from lines already known and the Ångström scale values determined from known second-order iron lines. Constant use of this iron calibration with zirconium and yttrium lines, along with Exner and Haschek's tables, leads me to think that the new wave-lengths may be relied upon to within 0.1 Angström unit. The intensities for the red spectrum are given, and show the comparative intensities for that part of the spectrum. When one value only for intensity is given it refers to the perpendicular component, and the omitted parallel component has about double the intensity. Exceptions to this are noted under some lines.

In Table *Ba*$_1$ are given the values of $\Delta\lambda/\lambda^2$ for lines observed by Runge and Paschen and remeasured by the author for a comparison of the accuracy obtainable. Barium has been found the poorest substance of the four studied for such a comparison.

TABLE Ba_1

H. G. R.	λ 4934 M.	2 N. K. R.	λ 4525 M.	2 N. G. R.	λ 4900 M.	H. K. R.	λ 4554 M.	I. N. K. R.	λ 5854 M.	I. N. S. R.	λ 4166 M.
−1.44	−1.45	−1.42	−1.44	−1.75	−1.83	−1.75	−1.83	−1.76	−1.76	−1.63	....
−0.74	−0.72	−0.76	−0.72	−1.09	−1.11	−1.08	−1.11	−1.19	−1.19	−1.16	....
+0.73	+0.71	+0.75	+0.74	−0.36	−0.35	−0.36	−0.35	−0.92	....	−0.88	−0.87
+1.45	+1.46	+1.45	+1.44	+0.35	+0.37	+0.35	+0.37	+0.58	−0.58	−0.62	....
				+1.07	+1.11	+1.06	+1.10	+0.58	+0.57	+0.55	....
				+1.75	+1.80	+1.79	+1.82	+0.91	....	+0.90	+0.87
								+1.19	+1.16	+1.14	....
								+1.76	+1.74	+1.70	....

In Table Ba_2, the line 6675.3 has its components in the ratio of ± .635 (0, 1, 3); the line 5997.4 may be represented by ± .55 (1, 2, 3); the line 5971.9 by ± .30 (2, 5); and the line 4580 possibly by ± .10 (4, 8, 15).

TABLE Ba_2

λ 6675.3			λ 5997.4			λ 5971.9			λ 4580		
i	$\Delta\lambda/\lambda^2$*		i	$\Delta\lambda/\lambda^2$		i	$\Delta\lambda/\lambda^2$ †		i	$\Delta\lambda/\lambda^2$	
5	−1.90	*s*	3	−1.64	*s*	8	−1.49	*s*		−1.54	*s*
1	−(0.64)	*p*	6	−1.10	*p*	10	−0.61	*p*		−0.81	*p*
1	0.00	*p*	3	−0.56	*s*	10	+0.60	*p*		−0.38	*s*
1	+(0.63)	*p*	3	+0.54	*s*	8	+1.49	*s*		+0.39	*s*
5	+1.90	*s*	6	+1.10	*p*					+0.81	*p*
			3	+1.66	*s*					+1.46	*s*

* The *s*-component of 6451 agrees with this, and possibly the parallel components, as the latter appears a broad weak band, rather than a single line.

† The *s*-components are broad and may resolve into two lines each. They are strongest at center. This is not usually the case with lines which resolve with better definition.

Table Ba_3 contains a list of triplets arranged in groups with like separation. The omitted parallel component is in the position of the line without field, i. e., with zero separation. Groups I, III, and IV stand in the simple ratio of 3 : 2 : 1. The separation in Group II differs from Group III by 1/11. The separation in Group III Professor Runge has designated the normal triplet "*a*" (see later in VIII, "Comparison of Substances"); or these groups are $3a/2$, a, $a/2$, and $12a/11$. Groups I, III, IV are represented in one single line 5997.4 excepting the zero component. Group I is also represented in 4166, Group II in 5854, and Group III also in 4554. In Table Ba_4 are the remaining lines of barium and under remarks are indicated

TABLE Ba_3

Group I			Group II		
λ	i	$\Delta\lambda/\lambda^2$	λ	i	$\Delta\lambda/\lambda^2$
6694.4*	5	∓1.66	6527.6†	12	∓1.24
6341.9	8	1.59	6148.6	3	1.17
4692.0		1.65	6141.9	30	1.20
4574.0		1.64	5778.0		1.22
4506.0		1.67	4416.0		1.18
4432.0		1.64	4131.0		1.18R
4414.0		1.62			1.18M
3889.4		1.68	3993.0†		1.24
			3071.7		1.17

Group III			Group IV		
λ	i	$\Delta\lambda/\lambda^2$	λ	i	$\Delta\lambda/\lambda^2$
6483.1	8	1.14	6653.7	4	0.55
6182.6	2	1.08	6611.8	8	0.56
6165.4†	2	1.06	6433.5	6	0.57
6063.3	12	1.10	6019.7	10	0.555
5988.1		1.09	4132.6		0.56
5826.0		1.12			
5536.0		1.11			
4727.0		1.11			
4283.0		1.07			
3935.0		1.09			
3501.0		1.11			

* The *s*-components are each nearly twice as strong as the *p*-components. In the other lines, the parallel components are the stronger.

† May possibly not belong in this group.

lines of several components which have the value of the triplet. It will be seen from these tables that the triplets look like lines of several components with some components suppressed. Or, what is more significant, the magnitude of the separations reduce to a few in number and recur in different types of separation. Runge has noted a vibration-difference per cm of 1691 in two pairs of lines. These pairs are 4166.24 and 3891.97; and 6497.07 and 5853.9. The longer wave-length of the first pair corresponds to the satellites of the first subordinate series, and the remaining line to the same series of shorter wave-length. In the second pair of lines the shorter wave-length is the satellite. The longer wave was not measured. The measurements here gave a value of ±0.93 for $\Delta\lambda/\lambda^2$, which is closer to the triplet value ±0.915 of the first adjacent series shorter wave-length than the value ±0.87 for λ 3892. The line λ 6487.7 possesses the

TABLE Ba_4

λ	i	$\Delta\lambda/\lambda^2$	Remarks
6687.5			Triplet. Too weak
6630.5			Triplet. Too weak
6595.55*	10	∓0.635	Compare 5854
6548.3	2	0.63	Compare 5854. Not *Cu* 3274.1 whose separation = 1.50
6498.9	8	1.48	
6497.1	20	0.93	
6495.3	2	0.68	Not *Cu* 3247.66 whose separation = 1.10
6484.7*	6	0.93	Not *Yt* 3242.43 whose separation = 1.33
6451.0†	3	1.89	
6435.2	4	1.29	8*a*/7 ?
6409.3	6		Broad. Not apparently separated
6403.1	4	0.84	
6398.84			Broad in appearance. Like several comp.
6200.3			Triplet. Too weak
6192.1	3	0.89	Compare 5854
6132.2	3	0.88	Compare 5854
6111.0	10	1.28	8*a*/7 ?
5519.0		1.02	
4600.0		1.53	Compare 4580
4403.0		1.28	
4350.0.		1.83	Compare 4554
3996.0		1.38	
3910.0		0.84	
3892.0		0.87	

* The *s*-component is approximately double the intensity of the *p*-component.

† See footnote * to Table Ba_1.

same separation as λ 6497.1 but is characterized by having the perpendicular components much stronger than the parallel. The separation of the triplet lines in Group II is the same as the separation of the middle line of the first adjacent series.

V. YTTRIUM

λ 3818.49			λ 4235.89		
i	$\Delta\lambda/\lambda^2$	A	i	$\Delta\lambda/\lambda^2$	A
2	−1.74 *s*	4×0.433	2	−(1.26) *s*	7×0.18
4	−1.29 *s*	3	2	−(0.89) *s*	5
10	−0.88 *p*	2	6	0.71 *p*	4
3	−0.85 *s*	2	2	−(0.54) *s*	3
2	−0.44 *p*	1	2	− 0.36 *p*	2
2	−0.42 *s*	1	2	+ 0.36 *p*	
2	+1.42 *s*			....	
2	+0.43 *p*		6	+ 0.71 *p*	
3	+0.84 *s*		....	....	
10	+0.88 *p*		....	....	b_o
3	+1.33 *s*				
2	+1.74 *s*				

The two lines on the preceding page have twelve and ten components respectively.

The following five lines have nine components each:

λ 4398.21

i	$\Delta\lambda/\lambda^2$	A
1+	−(1.72) *s*	9×0.19
2	− 1.33 *s*	7
6	+ 0.95 *s*	5
4	− 0.38 *p*	2
6	0.00 *p*	0
4	+ 0.38 *p*	
6	+ 0.95 *s*	
2	+ 1.34 *s*	
1	...... *s*	

λ 4199.46

i	$\Delta\lambda/\lambda^2$	A
6	−2.73 *s*	5×0.54
3	−1.58 *s*	3
6	−1.02 *p*	2
1+	−0.34 *s*	1
10	0.00 *p*	0
1+	+0.58 *s*	
6	+1.02 *p*	
3	+1.61 *s*	
6	+2.73 *s*	

λ 3950.51

i	$\Delta\lambda/\lambda^2$	A
8	−1.51 *s*	3×0.50
4	−0.98 *s*	2
20	−0.51 *p*	1
2	−0.49 *s*	1
15	0.00	0
2	+0.49 *s*	
20	+0.49 *p*	
4	+1.02 *s*	
8	+1.51 *s*	

λ 3628.89

i	$\Delta\lambda/\lambda^2$	A
10	−1.92 *s*	3×0.63
5	−1.27 *s*	2
8	−0.66 *p*	1
2	−0.64 *s*	1
10	0.00 *p*	0
2	+0.62 *s*	
8	+0.66 *p*	
5	+1.28 *s*	
10	+1.92 *s*	

λ 3584.71

i	$\Delta\lambda/\lambda^2$	A
12	−2.07 *s*	8×0.265
6	−1.32 *s*	5
10	−0.76 *p*	3
3	−0.55 *s*	2
15	0.00 *p*	0
3	+0.53 *s*	
10	+0.74 *p*	
6	+1.31 *s*	
12	+2.07 *s*	

At λ 4398.21 a common difference between components of the value 0.38 occurs six times. The interval in λ 4199.46 seems twice the interval in 3584.71, or the two lines may both have the smaller interval in different proportions. In each of the lines 3950.51 and 3628.89, there is a case of the *s*- and *p*-components occupying the same position.

The two following lines have eight components each:

λ 4236.10			λ 4083.89		
i	$-\Delta\lambda/\lambda^2$	A	*i*	$-\Delta\lambda/\lambda^2$	A
6........	−1.96 *s*	9×0.22	2........	(−1.79) *s*	9×0.20
2........	−1.53 *s*	7	3........	−1.119 *s*	6
3........	−0.65 *p*	3	6........	−0.83 *p*	4
3........	−0.22 *p*	1	1+......	−0.64 *s*	2
3........	+.... *p*		2........	+0.62 *s*	
3........	+.... *p*		6........	+0.83 *p*	
2........	+1.53 *s*		3........	+1.19 *s*	
6........	+1.96 *s*		1+......	(+1.75) *s*	

The three following lines are sextets:

λ 4358.91			λ 3747.70		
i	$-\Delta\lambda/\lambda^2$	A	*i*	$-\Delta\lambda/\lambda^2$	A
12........	−1.65 *s*	3×0.553	6........	−1.04 *s*	2×0.553
15........	−1.10 *p*	2	6........	−0.52 *s*	1
1........	−0.54 *s*	1	12........	−0.46 *p*	
1........	+0.54 *s*		12........	+0.46 *p*	
15........	+1.10 *p*		6........	+0.52 *s*	
12........	+1.65 *s*		6........	+1.04 *s*	

λ 3195.80		
i	$-\Delta\lambda/\lambda^2$	A
8........	−1.69 *s*	3×0.553
12........	−1.11 *p*	2
8........	−0.55 *s*	1
8........	+0.55 *s*	
12........	+1.11 *p*	
8........	+1.69 *p*	

Here are two lines, 4358.91 and 3195.80, accurate duplicates of each other—just the kind of agreement one would anticipate in the terms of a series. Unfortunately no other terms are present within the limits of observations. The *s*-components are of equal intensity and equidistant. They are removed from the null position one and three times the value ∓0.55. The *p*-components are twofold the same value.

In λ3747.70, the *s*-components are one and two times the value 0.52. Direct comparison of the *p*- and *s*-plates shows that the measured difference of the *p*-components and the inner *s*-components is actually present and not an error of observation. The law of multiple relationship mentioned on pp. 5 and 30 still holds for all components, if one goes so far as to take the small difference between these *p*- and inner *s*-components as a unit. The terms are then 7, 8, and 16 times the value ∓0.065.

The two following quintets could not be measured accurately:

λ 4477.1			λ 3951.76		
i	$\Delta\lambda/\lambda^2$	A	*i*	$\Delta\lambda/\lambda^2$	A
2........	−1.89 *s*	5×0.38	6........	− 1.47 *s*	4×0.38
....	...... *p*		1+......	− (.383) *p*	1
....	...... *p*		2........	0.00 *p*	0
....	...... *p*		1+......	+ (.377) *p*	
2........	+1.89 *s*		6........	+ 1.47 *s*	

These *p*-components are not separated in the first-order spectrum. As near as could be seen in the second-order spectrum, they are the same for both lines, and may be represented by 0 and 1 times the value ±0.38. The perpendicular components of λ 4477.10 are 5 times this value, and in λ 3951.76 they are 4 times it. The *s*-components of λ 3951.76 are diffuse inward, and suggest a pair of lines of value $\Delta\lambda/\lambda^2 = \pm 1.30$ which corresponds to a seven-fold multiple of 0.19. This only means a doubling of all the previous multiple factors.

The fourteen lines in the table on p. 13 are quadruplets. The line λ 4477.59 is an apparent quadruplet also, but too weak and diffuse to measure.

The lines λ 4475.90 and λ 3448.98 are very similar but do not belong to the same series, inasmuch as the blue line is much stronger instead of the reverse. The character of separation is reasonably similar in λ 4128.49 and λ 3930.84. The intensities, however, are out of all proportion to the expectations of the series law; they are what one could expect in two parallel series. It is especially noteworthy that the distances of the components of four lines are multiples of the value ±0.20 and the components of two lines multiples of the value ±0.30. Hence the components of the six lines are multiples of ±0.10.

Although such a division is striking, it may be remarked that if one chooses the multiple value small enough all lines would naturally

λ	i	$-\Delta\lambda/\lambda^2$	A	B
5510.10	2+	∓0.85 *s*	7×±0.12	
	3	∓0.48 *p*	4	
4682.50	12	1.40 *s*	7×±0.20	
	10	1.19 *p*	6	
4475.90	2	(1.44)	3×±0.50	
	3	0.52	1	
4375.11	100	1.07	5×±0.20	
	100	0.20	1	
4177.68*	100	1.00	5×±0.20	$D_r b$
	100	0.44	2	$D_r b$
4167.65	20	1.20	6×±0.20†	
	20	0.59	3	
4128.49	30	1.26	4× 0.30	$D_r w$
	30	0.29	1	$D_r w$
4106.60	50	....		b_o
	30	0.40		
3982.75	60	1.17	11× 0.105	D_r†
	60	0.53	5	
3930.84	50	1.21	4× 0.30	
	6–4	0.34	1	
3833.10	30	1.34	2× 0.67	
	25	0.70	1	
3552.87	..	....		r_o
	50	0.895		
3448.98	6	1.42	3× 0.50*	
	8	0.55	1	
3200.44	20	1.53	4× 0.37	
	20	0.69	2	

* The width of the *s*-components suggests two or more components.

† When the *p*- and *s*-components of this strong line are brought into juxtaposition under the microscope, the components are clearly not related in the 1-to-2 ratio. The 12-to-5 ratio times *a*/11 (see *infra*) seems more probable, but the 11-to-5 ratio here given agrees better with both the old and the new readings.

fall under the multiple proportions within the limits of error. Allowing an error of only 0.05 and all lines are at once multiples of 0.1. The same may be said of the before-mentioned multiple value 0.065, and no importance, within the limits of the present reading, can be attached to such small factors. The value 0.065, or more accurately 0.06, appeared as a difference of two components, which difference was actually present when one directly compared the two plates, and the striking feature was that all components of this line were multiples of this difference. So that although errors of larger magnitude may arise, the difference is still significant of the fact that the components of lines may stand in the very simple relation of multiples of small separations. In the remaining quadruplets there can be no question of .the presence of multiples of 0.20 and 0.30. There are no duplicates of the series character present.

The following 74 lines are triplets. The intensities of the undisturbed *p*-components are not given. The ratio of the intensity of the *s*- to the *p*-components is usually 1 to 2, though probably in many cases the ratio is nearer 2 to 5.

λ	*i*	$-\Delta\lambda/\lambda^2$	B	λ	*i*	$-\Delta\lambda/\lambda^2$	B
5663.1	12	∓1.10		3967.74	6	∓1.12	
30.3	2	0.74		44.90	7	1.34	n. i.
5582.1	4	0.97		06.57	5	1.48	
27.8	4–6	1.11		3878.80	15	2.34	n. i.*
5497.6	6	1.65		42.00	5	1.22	n. i.
66.7	8	1.03		3788.88	50	1.02	$D_r w$
03.0	6	0.79		82.50	15	1.38	
5205.9	10	1.18		76.73	15	1.49	
00.6	6	0.74		74.51	100	1.15	$D_r w$
5087.6	10	1.34		10.41	60	1.25	
4956.7	2+	0.48		3696.90	4	0.85	D
4900.3	20	1.10		68.67	6	1.38	
4883.9	20	1.24		64.76	30	1.74	$D_r w$
4855.1	15	0.92		45.67	8	1.30	n. i.
4840.1	3	1.50		35.60	5	1.16	D_r
4675.01	20	1.20		3633.28	50	1.02	
43.88	25	1.02		21.12	15	1.14	
4527.98	6	1.32		14.81	1+	(1.24)	
27.43	8	1.37		11.19	60	1.30	
06.12	15	0.92		02.12	40	0.62	
4465.50	35	1.06		00.90	75	1.48	
46.85	3	1.42		3593.11	8	0.91	
43.83	1+	....		87.86	5	1.12	
22.80	25	0.54		85.90	3		r_o
4348.91	8	1.27		49.21	50	1.67	
30.85	2	0.84		31.85	5	1.21	
09.81	50	1.33		3496.25	12	0.62	
4302.45	8	1.13		68.05	3	0.62	
4251.39	6	1.09		3372.93	6	1.25	
11.85	10	1.21		62.20	10	1.28	
04.84	20	1.61		28.11	30	1.08	
4174.27	30	1.25		20.10	1+	(1.26)	D
43.01	30	0.91	$D_r w$	3242.49	30	1.33	D
25.10	20	1.35		16.87	15	1.12	D_o
02.60	50	1.23		03.51	12	0.53	
4077.54	50	1.21		3173.40	5	1.23	
47.81	20	0.86		30.20	3–2	1.25	
40.00	15	1.57	D*i*				

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* *Y* λ 3878.47 is not present unless it should be this line, which is scarcely credible. λ 3878.80 is certainly in satisfactory agreement with the iron line λ 3878.78. But much stronger iron lines come out as impurities on the plates with much smaller intensities. The separation is unlike any other line of the triplet class in yttrium. The separation of *Fe* λ 3878.78 is unknown to the author but should the separation of the *Fe* line prove to be some other magnitude, then the present line might safely be regarded as an yttrium line, i. e., the magnetic separation may be used to determine the substance of doubtful lines. See also remarks upon *Ba* λ 6548.3, λ 6495.3, and λ 6484.7 (Table Ba_4).

Every line in the triplet class is some small multiple of the simple values given with the lines having several components. Many of the lines, however, could safely be different multiples of more than one of these values. It is therefore of no significance so to classify the lines; e. g., a great many triplets have values approximately 1.25. If we assume 0.05 as a possible error, then any value between 1.20 and 1.30 must be considered. We then may have within these limits multiples of the intervals 0.18, 0.20, 0.30, 0.43, and 0.63. Further, if multiple relations hold and one attempts to find series in the triplet class, one is confronted by the fact that triplets of a certain magnitude may belong to quite different groups. As per above illustration, five triplets of separation 1.25 could belong to as many different groups. When we consider further the small differences in the triplets here noted, it is seen that types exist whose difference in separation is so small that a very small error in observation would place a line in a wrong type. These two considerations indicate that, if present in triplets, series can be found only with great labor; whereas in other types of separation they are, by Preston's law, at once apparent, if present at all.

VI. ZIRCONIUM

The following two lines have eleven components each:

λ 3573.30			λ 3272.39		
i	$\Delta\lambda/\lambda^2$	A	i	$\Delta\lambda/\lambda^2$	A
5	−2.24 *s*	6×0.37	5	−2.26 *s*	6×0.37
3	−1.50 *s*	4	2	−1.54 *s*	4
3	−1.11 *p*	3	3	−1.11 *p*	3
1	−0.74 *s*	2	1	...... *s*	2
6	−0.34 *p*	1	5	−0.37 *p*	1
1	...... *s*	0	1	...... *s*	0
6	+0.34 *p*		5	+0.37 *p*	
1	...... *s*		1	+.... *s*	
3	+1.03 *p*		3	+1.14 *p*	
3	+1.50 *s*		2	+1.50 *s*	
?	+.... *s*	b_o	5	+2.26 *s*	

These two lines are certainly duplicates. The *s*-components are even multiples of 0.37 and the *p*-components are odd multiples of the same value. A common difference of 0.74 occurs six times in each of these lines.

The following two lines have nine components each:

λ 3780.78			λ 3921.99		
i	$\Delta\lambda/\lambda^2$	A	*i*	$\Delta\lambda/\lambda^2$	A
6	−2.17 *s*	5×0.43	4	−2.14 *s*	5×0.43
2	−1.69 *s*	4	1	......	
2	−0.86 *p*	2	2	−0.92 *p*	2
3	−0.42 *p*	1	3	−0.44 *p*	1
3	0.00 *p*	0	3	0.00 *p*	0
3	+0.48 *p*		2	+0.46 *p*	
1+	+0.90 *p*		1+	+0.91 *p*	
2	+1.69 *s*		1	......	
6	+2.17 *s*		4	+2.14 *s*	

These lines are duplicates and the separations are multiples of the value 0.43.

The following six lines have eight components each:

λ 4440.80			λ 4268.22		
i	$\Delta\lambda/\lambda^2$	A	*i*	$\Delta\lambda/\lambda^2$	A
2	−2.14 *s*		10	−2.16 *s*	4×0.54
4	−1.57 *s*		8	−1.09 *p* ⎫	2
2	−1.04 *s*		6	−1.07 *s* ⎭	
15	−0.89 *p*		3 *s* ⎫	0.00	
15	+0.89 *p*	9×0.10	12 *p* ⎭		
2	+0.98 *s*	10	8	1.07 *p* ⎫	
4	+1.57 *s*	16	6	1.12 *s* ⎭	
2	+2.18 *s*	22	10	2.16 *s*	

λ 4214.05			λ 4027.4		
i	$\Delta\lambda/\lambda^2$	A	*i*	$\Delta\lambda/\lambda^2$	A
6	−1.76 *s*	3×0.60	2	−1.94 *s*	7×0.27
6	−1.21 *p*	2	3	−1.36 *s*	5
2	−1.17 *s*	2	8	−1.09 *p*	4
10 *p* ⎫	0.00		2	−0.75 *s*	3
1 *s* ⎭			2	+0.87 *s*	
6	+1.07 *p*	0	8	+1.09 *p*	
2	+1.13 *s*		3	+1.37 *s*	
6	+1.75 *s*		2	+1.94 *s*	

λ 3764.6			λ 3459.1		
i	$\Delta\lambda/\lambda^2$	A	i	$\Delta\lambda/\lambda^2$	A
2	1.82 *s*	7×0.27	3	−2.20 *s*	22×0.10
3	1.35 *s*	5	4	−1.51 *s*	15
8	1.08 *p*	4	8	−1.17 *p*	12
2	0.86 *s*	3	2	−0.73 *s*	7
1+	0.86 *s*		3	+0.68 *s*	7
8	1.08 *p*		8	+1.17 *p*	12
3	1.35 *s*		4	+1.54 *s*	15
1+	1.89 *s*		1+	+2.28 *s*	23

λ 4027.4 and λ 3764.6 are probably duplicates.

The following seven lines have seven components each:

λ 4457.71			λ 4258.31		
i	$\Delta\lambda/\lambda^2$	A	i	$\Delta\lambda/\lambda^2$	A
2	−2.31 *s*		4	−1.53 *s*	6×0.26
10	−1.46 *s*		6	−1.37 *p*	5 (?)
10	−1.33 *p*		2	−(0.82) *p*	3
2	0.00 p*		10	0.00	0
10	+1.46 *s*		2	+(0.82) *p*	8×0.10
10	+1.50 *p*		6	+ 1.37 *p*	14
2	+2.31 *s*		4	+ 1.48 *s*	15

λ 4171.65 †			λ 4093.32		
i	$\Delta\lambda/\lambda^2$	A	i	$\Delta\lambda/\lambda^2$	A
8	−1.48 *s*	6×0.25	1+	−1.77 *s*	6×0.305(?)
8	−1.26 *p*	5	2	−0.90 *p*	3
6	−0.26 *s*	1	2	−0.67 *s*	2?
6	0.00 *p*	0 (?)	3	0.00 *p*	0
6	+0.26 *s*		3	+0.66 *s*	7×0.10
4	+1.24 *p*		2	+0.93 *p*	9
3	+1.50 *s*		1+	+1.78 *s*	18
2	+(3.02) *s*	12 (?)(*a*)			

λ 4068.9			λ 4055.2		
i	$\Delta\lambda/\lambda^2$	A	i	$\Delta\lambda/\lambda^2$	A
2	−1.55 *s*		2	−1.11 *s*	2×0.53
2	−1.16 *p*		6	−0.56 *p*	1
2	−0.49 *s*		8	−0.53 *s*	1
6	0.00 *p*‡		8	0.00 *p*	0
2	+0.49 *s*		4	+0.49 *p*	
2	+0.83 *p*		8	+0.53 *s*	
2	+1.55 *s*		2	+1.11 *s*	

λ 3368.01

i	$\Delta\lambda/\lambda^2$	A
1	−1.71 *s*	4×0.43
8	−1.25 *p*	3
2	−0.88 *s*	2
3	0.00 *p*	0
2	+0.88 *s*	
8	+1.26 *p*	
1+	+1.68 *s*	

* The weak middle *p*-component is unsymmetrical.

† The line is unsymmetrical in intensity and has a possible extra component (*a*) upon the violet side This line may be also a foreign line as it does not appear upon the plates with weaker fields.

‡ The outer weak pair of *p*-components is not symmetrical.

The following sixteen lines have six components each:

λ 4590.81

i	$\Delta\lambda/\lambda^2$	A
2	−1.74 *s*	3×0.55
6	−1.11 *p*	2
2	−0.55 *s*	1
2	+0.55 *s*	
5	+1.11 *p*	
2	+1.67 *s*	

λ 4438.23

i	$\Delta\lambda/\lambda^2$	A
2	−1.57 *s*	3×0.52
6	−1.07 *p*	2
2	−0.57 *s*	1
2	+0.55 *s*	6?×0.10
6	+1.07 *p*	11
2	+1.60 *s*	16

λ 4431.70

i	$\Delta\lambda/\lambda^2$	A
6	−2.73 *s*	5×0.55
6	−1.67 *s*	3
12	−1.12 *p*	2
12	+1.12 *p*	
6	+1.67 *s*	
6	+2.74 *s*	

λ 4403.67

i	$\Delta\lambda/\lambda^2$	A
5	−2.11 *s*	8×0.26
15	−0.76 *p*	3
12	−0.48 *s*	2
12	+0.48 *s*	
15	+0.76 *p*	
5	+2.11 *s*	

λ 4110.29

i	$\Delta\lambda/\lambda^2$	A
6	−1.54 *s*	4×0.39
8	−1.17 *p*	3
1+	−0.77 *s*	2
1+	+0.77 *s*	
8	+1.17 *p*	
6	+1.54 *p*	

λ 4040.49

i	$\Delta\lambda/\lambda^2$	A
2	−2.08 *s*	8×0.26
10	−0.77 *p*	3
8	−0.51 *s*	2
8	+0.51 *s*	
10	+0.77 *p*	
2	+2.12 *s*	

λ 3554.31		
i	$\Delta\lambda/\lambda^2$	A
2	−2.67 *s*	6?×0.43
6	−1.72 *s*	4
10	−0.42 *p*	1
10	+0.42 *p*	4×10
6	+1.72 *s*	17
2	+2.67 *s*	27

λ 3507.80		
i	$\Delta\lambda/\lambda^2$	A
6	− 2.78 *s*	?
1+	−(1.05) *s*	
5	− 0.90 *p*	
5	+ 0.90 *p*	
1+	+(1.08) *s*	
6	+ 2.75 *s*	

λ 3498.00		
i	$\Delta\lambda/\lambda^2$	A
8	−2.51 *s*	5×0.50
2	−1.48 *s*	3
12	−0.44 *p*	1?
12	+0.44 *p*	
2	+1.48 *s*	
8	+2.45 *s*	

λ 3483.70		
i	$\Delta\lambda/\lambda^2$	A
4	−1.82 *s*	5×0.36
16	−1.08 *s*	3
20	−0.38 *p*	1
20	+0.38 *p*	
16	+1.08 *s*	
4	+1.80 *p*	

λ 3482.96		
i	$\Delta\lambda/\lambda^2$	A
4	−1.10 *s*	3×0.36
4	−0.72 *p*	2
4	−0.70 *s*	2
4	+0.70 *s*	
6	+0.72 *p*	
4	+1.10 *s*	

λ 3396.51		
i	$\Delta\lambda/\lambda^2$	A
2	−1.06 *p*	3×0.34
6	−0.67 *s*	2
6	−0.33 *p*	1
6	+0.33 *p*	
6	+0.67 *s*	
2	+0.95 *p*	

λ 3323.21		
i	$\Delta\lambda/\lambda^2$	A
8	− 1.91 *s*	5×0.38
2	−(1.15) *s*	3
12	− 0.41 *p*	1
12	+ 0.41 *p*	
2	+(1.15) *s*	
8	+ 1.91 *s*	

λ 3318.70		
i	$\Delta\lambda/\lambda^2$	A
	−(1.53) *s*	
1+	−(1.72) *s*	
5	− 0.69 *p*	
5	+ 0.69 *p*	
1+	+(0.74) *s*	
5	+ 1.45 *s*	

λ 3313.89		
i	$\Delta\lambda/\lambda^2$	A
1+	−(2.39) *s*	6×0.40
8	− 1.69 *s*	4
6	− 0.40 *p*	1
6	+ 0.40 *p*	4×0.10
8	+ 1.68 *s*	17
1+	+(2.39) *s*	24

λ 3155.90		
i	$\Delta\lambda/\lambda^2$	A
2	−2.10 *s*	8×0.26
6	−0.77 *p*	3
8	−0.51 *s*	2
8	+0.51 *s*	
6	+0.77 *p*	
2	+2.10 *s*	

The following eleven lines have five components each:

λ 5350.5		
i	$\Delta\lambda/\lambda^2$	A
8	−1.42 *s*	3×0.48
4	−0.49 *p*	1
2	0.00 *s*	0
3	+0.49 *p*	
4	+1.44 *s*	

λ 4236.23		
i	$\Delta\lambda/\lambda^2$	A
8	−1.47 *s*	
2	−0.66 *p*	
4	0.00 *p*	
2	+0.66 *p*	
8	+1.47 *s*	
2	(2.20) ? *s*	

λ 4187.30		
i	$\Delta\lambda/\lambda^2$	A
5	−2.92 *s*	9×0.32
4	−1.26 *p*	4
8	0.00 *p*	0
4	+1.24 *p*	
5	+2.92 *s*	

λ 4061.70		
i	$\Delta\lambda/\lambda^2$	A
10	−1.79 *s*	7×0.26
4	−0.52 *p*	2
6	0.0 *p*	0
3	+0.51 *p*	
10	+1.79 *p*	

λ 4046.30		
i	$\Delta\lambda/\lambda^2$	A
2	−1.65 *s*	2×0.83
4	−0.84 *p*	1
8	0.00 *s*	0
4	+ .... *p*	
2	+1.65 *s*	

λ 3501.50		
i	$\Delta\lambda/\lambda^2$	A
6	− 2.00 *s*	3×0.67
4	−(0.70)	1
2	0.00 *s*	0
2	+(0.70) *p*	7×0.10
4	+ 2.00 *s*	20

λ 3471.31		
i	$\Delta\lambda/\lambda^2$	A
6	−0.87 *s*	9×0.10
12	−0.30 *p*	3
6	+0.30 *p*	3
4	+0.49 *s*	5
2	+1.20 *s*	12

λ 3432.59		
i	$\Delta\lambda/\lambda^2$	A
2	−1.71 *s*	
8	−0.94 *p*	
15	0.0 *s*	
8	+0.94 *p*	
2	+1.71 *s*	

λ 3376.42		
i	$\Delta\lambda/\lambda^2$	A
2	−1.10 *s*	3×0.37
2	−0.38 *p*	1
10	0.00 *s*	0
2	+0.38 *p*	
1+	+1.17 *s*	

λ 3271.30		
i	$\Delta\lambda/\lambda^2$	A
2	−(1.38) *s*	
8	− 0.63 *p*	
12	0.00 *s*	
8	+ 0.63 *p*	
2	+(1.38) *s*	

λ 3099.42

i	$\Delta\lambda/\lambda^2$	A
1+......	......	
5........	−1.31	
3........	0.0	
5........	+1.31	
1+......	......	

The line λ 5350.5 is unsymmetrical in intensity; λ 3471.31 is unsymmetrical in intensity as well as in separation. Duplicates are not present.

The following eighty-nine lines have four components each:

λ	i	$\Delta\lambda/\lambda^2$	A	λ	i	$\Delta\lambda/\lambda^2$	A
4582.50	3	∓1.02*s*	2×0.51	4036.10	20	∓1.30	4×0.33
	2	0.52*p*	1		20	0.67	2
4456.50	30	0.83	3×0.28	4034.30	6	1.33	4×0.33
	30	0.56	2		4	0.32	1
4455.64	2	1.20	3×0.42	4031.57	2	1.66	4×0.42
	2	0.84	2		3	0.41	1
4455.08	12	1.21	3×0.42	4025.16	25	(1.39)	
	15	0.46	1		25	0.73	
4429.28	3	1.58	3×0.51	4024.20	25	1.54	3×0.51
	5, 3	0.49	1		20	0.55	1
4420.70	15	1.82		4017.16	6	1.13	3×0.42
	15	0.71			8	0.43	1
4414.80	20	1.58	5×0.32	4004.51	2	1.00	5×0.20
	20	0.63	2		5	0.79	4
4413.28	12	1.76		4003.28	8, 10	2.05	7×0.29
	15	0.53			6, 4	0.29	1
4394.73	....	....		3999.18	100	1.17	3×0.42
	7, 5	0.60			100	0.85	2
4349.10	2	(1.23)	3×0.40	3973.68	20	1.14	2×0.57
	2	0.77	2		15	0.57	1
4312.47	4	1.27	3×0.42	3934.99	20	1.14	2×0.57
	4	0.41	1		15	0.57	1
4309.20	8	1.25	3×0.42	3916.16	25	0.85	4×0.22
	8	0.85	2		20	0.24	1
4256.66	6	1.50	6×0.25	3894.00	5, 3	(0.89)	4×0.22
	6, 4	0.27	1		2, 4	(0.67)	3
4224.42	....	....		3891.61	25	1.28	13×0.10
	5	1.08			25	0.70	7
4199.30	15	1.47	3×0.48	3890.58	30	1.29	4×0.30
	12	0.46	1		30	0.29	1
4077.27	....	....		3817.80	30, 20	0.81	
	5	0.38			20	0.35	
4071.30	8	1.68		3782.45	3, 5	(0.72)	
	10	0.58			7	0.73	
4043.77	15	1.48	3×0.50	3674.98	50	0.63	3×0.21
	15	0.54	1		50	0.42	2

λ	i	$\Delta\lambda/\lambda^2$	A	λ	i	$\Delta\lambda/\lambda^2$	A
3663.81	20	$\mp$1.27	3×0.42	3394.96	4	$\mp$1.76	
	15, 12	0.42	1		4	0.94	
3650.90	6	1.49	2×0.75	3378.47	4	....	
	5	0.76	1		4	1.43	
3634.33	10	1.36	4×0.34	3377.61	8	1.45	
	10, 6	0.35	1		6, 4	0.61	
3629.29	2	1.09		3369.42	4	1.64	4×0.42
	2	0.71			4	0.44	1
3624.10	25	1.16		3364.00	8	1.33	3×0.42
	25, 20	0.33			8	0.84	2
3613.30	40	(1.03)		3357.42	25, 20	0.59	3×0.20
	30	0.95			25, 20	0.40	2
3612.61	3	0.59		3338.07	4	1.98	
	3	0.41			2	1.17	
3588.15	20	0.58	2×0.29	3310.10	4	....	
	20	0.29	1		4	1.45	
3578.40	20	2.01	7×0.29	3296.59	6	1.49	3×0.50
	20, 15	0.28	1		4	(0.47)	1
3569.03	2	....		3287.46	2	....	
	2	0.47			2	0.54	
3568.32	6	1.17	4×0.30	3284.89	20	0.65	2×0.33
	6	0.90	3		20	0.35	1
3552.20	50	1.27	3×0.42	3274.14	4	1.46	2×0.75
	50	0.77	2?		4	0.78	1
3530.17	6	1.21	3×0.42	3264.96	4	1.46*s*	3×0.50
	5, 4	0.45	1		4	(0.51)*p*	1
3514.79	4	1.23	3×0.42	3229.00	15	1.36	3×0.45
	4	0.84	2		15, 12	0.46	1
3505.67	60	1.67	4×0.42	3213.01	4	1.10	2×0.53?
	60	0.41	1		4	0.50	1
3480.59	15	1.57	3×0.51?	3182.15	....	....	
	15	0.98	2		5	0.67	
3478.98	2	(0.87)		3181.79	8	1.56	
	6	0.50			8	1.45	
3470.10	2	(1.59)	6×0.27	3178.30	8	1.65	4×0.42
	4	1.33	5		8	0.87	2
3460.10	2, 3	(1.22)		3166.48	....	....	
	3	0.72	2		6	0.61	
3454.71	3	0.61	1×0.60	3165.68	4	1.60	
	4	1.18	2		4	0.49	
3440.54	5	0.+*s*	*p*>*s*	3164.54	12	1.09	11×0.10
	6	1.11*p*			6	0.40	4
3437.30	25	1.42	2×0.71	3157.19	6	1.16	3×0.42?
	25	0.72	1		3	0.81	2
3434.08	5	1.58	4×0.39	3111.09	4	1.46	
	10	1.19	3		6	0.55	
3424.97	4	0.93	2×0.42?	3095.29	8	1.25	5×0.25
	10, 8	0.41	1		8	0.76	3
3413.55	2	(1.55)	13×0.12	3031.04	3	....	
	4	1.43	12		2	0.66	

A simple relationship between the components of a line appears for a great majority of these quadruplets. The interval 0.42 repeats itself very often in many lines, but the factors by which this interval must be multiplied in order to obtain the separation of the lines are different, so that few duplicates occur. Some of the lines are evidently pairs. A well-defined line, λ 4455.08, the distance of whose components are three and one times the value 0.42, is accompanied on the red side by a weak line whose separation is three and one times the same value 0.42. The difference in vibration-frequency of these two lines is 2.62. λ 3663.81 is a duplicate of λ 4455.08, but is not accompanied by a weak line. There are two pairs of lines whose separation is in the ratio of three to one for the pair of greater wave-length, and in the ratio of three to two for the pair of shorter wave-length. This first pair is λ 4312.47 and λ 4309.20 with a vibration difference of 12.21. The second pair is λ 3530.17 and λ 3514 with a vibration difference of 123.95. One can associate with the last pair the very strong line λ 3507.67, whose components have the separation of four and one times the value 0.42. There appears also another pair whose components stand in the ratios of three to one and four to one times the value 0.42. These lines are λ 3364 and λ 3369.42, which gives a vibration difference 47.82. In the lines λ 3164.54 and λ 3157.19 there exist possibly the ratios of three to one and three to two times the value 0.42 respectively. The vibration difference is 73.46. These differences in vibration have no uniformity, such as one expects in corresponding terms of similar series. It is possible that λ 3999.18, the strongest line of the spectrum, and λ 3552.2 belong to the three to two multiples of 0.42, but this value does not repeat itself in other strong lines.

The zirconium triplets have not been thoroughly investigated for series. Such an investigation of so many lines would require a long time. For reasons given in the discussion of yttrium triplets, and here even more pronounced, the application of Preston's law is neither immediate nor direct, and the necessary work would be enormous. However, I have investigated the separations 0.59±0.07, 0.76±0.07, 0.84±0.08, 1.25±0.07, 1.66±0.07, 1.82±0.09, and 2.34.

The following four hundred and ten lines are triplets:

λ	i	$\Delta\lambda/\lambda^2$	λ	i	$\Delta\lambda/\lambda^2$
5665.4	2, 4	(∓1.25)	4542.49	12, 25	∓1.59
36.0	1+, 3	(0.83)	40.19	2, 6	(1.31)
5504.7	6, 12	0.59	36.00	10, 20	0.94
02.5	6, 12	0.99	23.44	3, 6	1.35
5492.1	5, 10	0.83	07.39	8, 15	1.10
69.8	8, 16	0.56	4497.27	30, 60	0.94
65.8	1+, 3	(1.01)	94.78	15, 30	1.20
53.8	6, 12	0.66	85.71	2, 4	(2.35)
46.0	6, 10	0.76	82.72	4, 8	1.24
00.7	8, 15	0.68	81.00	5, 10	1.28
5385.6	8, 15	1.24	70.80	10, 20	1.08
57.5	8, 15	0.66	68.98	3, 8	1.29
5191.7	10, 20	1.30	67.12	6, 12	1.53
43.5	6, 12, 8	0.62	61.50	8, 15	1.18
38.4	10, 20	0.62	60.57	2, 4	1.27
14.2	2, 4	(0.90)	50.71	5, 10	2.73
5079.6	1+, 3	(0.62)	43.41	30, 60	1.07
66.9	2, 5	0.95	29.55	1+, 3	(1.61)
4839.3	2, 5, 4	0.75	27.44	8, 15	1.09
28.5	4, 6, 3	0.70	04.98	6, 12	1.44
24.8	4, 8	1.27	4383.90	6, 12	1.31
16.1	12, 24	0.78	80.12	50, 100	1.15
10.0	4, 8	1.19	73.28	1+, 3	(2.32)
06.5	4, 8	1.27	71.27	20, 40	1.18
4789.3	3, 6	0.95	66.69	15, 30	1.22
85.6	6, 12	0.99	61.01	6, 12	1.62
72.1	15, 30	0.90	60.05	50, 100	1.26
62.8	2, 4	1.13	58.95	5, 10	1.32
39.6	20, 4	1.04	48.15	50, 100	1.12
19.3	8, 16	1.17	46.70	5, 10	0.84
12.2	3, 6	1.31	43.59	1+, 3	(1.23)
10.3	25, 50	1.18	43.23	2, 4	1.06
03.3	2, 4	(1.41)	41.40	5, 10	1.36
4688.7	5, 8	1.14	39.80	3, 6	1.86
88.0	30, 60	1.32	37.90	8, 15	1.34
85.5	3, 8	1.11	33.59	15, 30	1.24
83.6	8, 16	1.19	24.24	8, 15	1.06
67.4	1+, 3	(1.24)	19.24	4, 8	1.24
62.0	3, 8	1.05	17.57	12, 25	1.26
57.9	4, 8	1.18	09.99	4, 8	1.68
45.01	6, 12	0.76	04.92	8, 15	1.45
34.20	15, 30	1.09	03.12	20, 40	1.67
29.33	6, 12	1.20	02.80	2, 4	1.67
26.62	8, 15	1.21	02.10	8, 16	0.88
14.20	6, 12	1.03	4297.00	12, 25	1.50
04.59	3, 6	2.34	95.08	25, 50	1.69
02.80	10, 20	1.27	93.41	15, 30	0.75
4584.44	1+, 3	(1.02)	91.54	5, 10	1.63
76.37	1+, 3	0.71	91.38	4, 8	1.62
75.78	15, 30	0.91	86.78	6, 12	0.76
74.78	6, 12	0.94	82.53	8, 15	1.82
65.68	3, 6	0.95	77.60	6, 12	1.42
54.29	8, 16	1.10	76.91	6, 12	1.67
53.25	3, 6	0.54	74.95	6, 12	1.20

λ	i	$\Delta\lambda/\lambda^2$	λ	i	$\Delta\lambda/\lambda^2$
4265.17	4, 8	∓1.52	4078.49	6, 12, 8	∓1.66
61.65	6, 12	1.11	76.70	8, 15	1.26
61.42	2, 5	(1.90)	75.09	12, 20	1.67
53.76	8, 15	2.14	72.90	40, 75	1.27
43.74	2, 4	(1.44)	64.38	25, 50	1.05
41.98	20, 40	1.27	60.78	6, 10	1.03
41.50	15, 30	1.11	58.78	4, 8	0.88
39.58	30, 20	1.49	55.90	15, 25	1.32
37.57	4, 8	2.18	54.60	2, 4	0.56
36.81	6, 12	(0.85)	50.52	30, 50	1.37
34.89	8, 16	1.25	48.90	30, 50	1.34
31.88	10, 20	1.34	45.90	25, 40	0.61
27.98	40, 60	1.51	42.49	8, 15	(1.38)
22.67	4, 8	0.70	41.90	10, 20	(1.64)
18.60	4, 8	1.86	30.87	2, 4	0.96
15.95	4, 8	0.84	29.88	30, 50	1.77
15.50	6, 12	1.42	29.17	6, 12	1.74
12.17	25, 50	0.62	24.70	20, 40	(1.39)
11.50	4, 8	1.57	18.60	15, 30	1.02
10.87	10, 20	1.57	12.48	8, 15	0.94
09.21	50, 100	0.97	07.80	10, 20	1.08
01.69	20, 50	1.69	05.02	6, 12	(1.57)
4196.32	8, 15	1.35	3991.31	100, 150	1.08
95.00	10, 20	1.84	89.65	10, 15	1.33
94.66	2, 4	1.20	84.90	10, 20	1.57
92.03	4, 8	(1.14)	81.79	20, 40	1.35
91.75	3, 5	0.77	78.86	6, 12	1.47
87.80	20, 30	1.60	78.35	2, 4	(1.04)
86.89	20, 30	1.63	77.60	10, 20	1.06
83.51	10, 20	1.77	75.47	12, 30	1.22
80.08	25, 40	1.40	68.39	10, 20	1.16
68.90	6, 10	1.28	66.80	10, 20	1.69
66.60	15, 30	1.50	61.71	12, 25	1.29
61.48	30, 50	0.71	58.39	75, 125	0.98
53.96	8, 15	2.38	56.90	3, 6	0.62
52.87	15, 30	1.59	41.75	10, 15, 8	1.01
51.23	20, 50	1.39	36.28	12, 25	1.88
49.43	150, 300	1.27	31.55	2, 4	+1.66
47.53	6, 10	1.20	29.71	30, 50	1.14
40.70	5, 10	1.86	26.96	3, 6	1.19
38.02	6, 10	0.33	20.35	2, 4	(1.67)
35.85	10, 20	1.50	18.25	1+, 3	(0.50)
34.46	4, 8	(1.66)	16.80	6, 12	1.42
21.68	12, 20	1.70	14.59	10, 20	0.94
08.60	10, 20	1.67	00.08	2, 4	(1.65)
07.75	6, 10	0.99	3897.82	5, 10	1.43
4099.50	4, 6	(1.89)	96.73	10, 20	1.18
96.80	15, 30	0.90	92.19	6, 12	1.21
94.42	6, 10	1.46	85.61	12, 25	1.11
91.00	6, 10	0.66	79.21	10, 20	1.35
90.70	30, 50	0.91	77.78	12, 25	1.10
89.98	8, 15	1.00	64.57	25, 50	1.32
87.88	5, 10	1.74	64.12	30, 50	1.20
84.50	8, 15	1.18	49.48	15, 25	1.35
83.29	6, 12	1.58	47.22	12, 20	1.28
81.48	30, 50	1.33	43.30	25, 50	1.05

λ	i	$\Delta\lambda/\lambda^2$	λ	i	$\Delta\lambda/\lambda^2$
3836.98	75, 150	∓1.24	3566.30	15, 25	∓1.23
36.18	25, 50	0.76	65.51	10, 20	0.93
22.60	15, 30	0.85	59.23	6, 10	0.80
00.91	5, 10	1.44	56.89	75, 125	0.94
3796.71	30, 50	1.80	50.67	8, 20	1.40
92.55	10, 20	1.38	49.73	20, 30	1.60
91.60	15, 25	1.52	47.90	20, 30	1.39
86.80	4, 8	1.34	42.87	40, 60	1.23
82.99	3, 6	(0.92)	39.17	5, 8	1.77
82.45	3, 6	(0.72)	37.11	10, 15	1.24
72.29	10, 20	1.55	35.30	6, 10	1.28
66.99	50, 100	1.15	33.35	12, 20	1.83
59.30	3, 6	1.27	31.00	10, 20	1.17
57.99	12, 25	1.31	27.58	15, 25	1.19
51.85	75, 150	1.02	26.00	25, 40	1.70
50.84	10, 20	1.30	21.01	12, 20	1.93
46.18	50, 100	1.19	19.72	25, 40	1.19
38.32	6, 10	1.47	10.61	8, 12	1.72
37.54	4, 8	1.03	09.48	20, 30	1.23
35.15	12, 20	1.52	06.23	10, 15	1.89
31.50	30, 50	0.97	05.88	75, 125	(1.44)
29.98	8, 15	1.87	00.33	5, 10	1.04
27.90	15, 20	1.60	3499.78	20, 30	1.64
19.02	8, 12	1.59	96.40	60, 100	1.10
14.99	30, 50	1.46	83.17	3, 5	(1.38)
14.30	6, 10	2.05	81.36	50, 100	1.19
09.51	40, 75	1.20	79.58	10, 15	(1.07)
3698.41	75, 125	1.26	78.68	8, 12	1.63
97.70	20, 40	1.28	78.45	6, 10	1.74
79.80	1+, 3	(1.37)	63.23	30, 50	1.05
79.10	15, 25	1.24	61.22	6, 10	1.38
72.81	3, 5	2.85	57.75	25, 30	1.33
71.49	25, 40	0.99	57.30	2, 3	(1.98)
68.69	15, 25	1.73	56.02	3, 5	0.59
67.28	6, 12	1.32	47.50	10, 15	0.66
62.32	10, 20	0.95	46.71	5, 8	0.88
61.10	3, 5	0.57	43.69	10, 15	0.71
55.72	8, 15	1.74	40.70	2, 3	(1.35)
53.61	2, 4	1.17	38.39	100, 150	1.25
51.65	2, 4	(1.44)	30.73	40, 40	1.32
36.69	15, 25	1.69	27.23	1+, 3	(1.76)
33.70	12, 20	1.29	24.00	2, 4	1.49
30.30	20, 40	1.89	19.76	3, 6	0.81
19.22	6, 12	0.83	19.22	6, 6	2.02
12.13	30, 50	1.44	14.87	15, 15	0.86
07.60	15, 30	1.48	10.44	30, 25	1.24
01.40	40, 75	1.24	08.23	12, 10	0.52
00.11	10, 15	1.11	05.04	25, 20	0.98
3588.96	3, 6	1.71	03.89	12, 10	0.60
88.51	12, 20	1.66	03.10	10, 8	1.69
86.42	15, 20	0.75	3399.95	1+, 3	(1.61)
77.74	5, 8	1.16	99.51	10, 15	0.63
77.10	50, 75	1.39	96.81	2, 3	1.06
75.89	15, 25	1.35	94.96	3, 5	1.76
72.70	75, 125	1.04	93.36	15, 12	1.62
70.25	6, 12	1.11	92.20	75, 75	1.26

λ	i	$\Delta\lambda/\lambda^2$	λ	i	$\Delta\lambda/\lambda^2$
3388.49	40, 40	∓1.63	3234.24	10, 12	∓1.19
88.07	40, 40	0.75	31.89	40, 50	1.71
83.90	2, 4	0.89	29.00	15, 20	1.37
74.84	30, 15	1.50	22.61	8, 10	1.28
73.61	15, 8	1.04	14.35	40, 50	1.70
73.05	4, 6	1.05	12.17	8, 12	1.12
70.73	4, 6	1.53	3192.11	8, 12	1.27
61.35	4, 6	1.15	91.31	4, 6	0.93
60.61	4, 6	1.50	83.08	30, 40	1.14
60.18	12, 10	1.03	61.12	2, 4	0.94
56.28	25, 20	1.73	57.94	4, 8	0.96
54.59	12, 10	1.48	38.88	20, 30	1.14
49.59	4, 4	1.12	37.08	2, 4	(1.43)
49.23	2, 2	1.02	33.70	15, 20	1.17
45.00	15, 15	1.14	32.22	2, 4	(1.09)
44.00	1+, 3	1.18	29.96	20, 30	1.01
42.10	1+, 3	1.09	29.38	20, 30	0.95
27.05	15, 12	1.26	26.10	15, 20	0.55
19.19	8, 6	1.63	25.33	1+, 3	(1.03)
11.53	3, 3	1.73	20.90	4, 8	1.32
06.48	30, 20	1.11	11.09	6, 10	1.46
05.33	25, 25	1.39	06.79	25, 40	1.32
02.89	8, 6	1.43	3055.00	15, 25	1.20
3288.99	12, 10	1.92	36.57	8, 12	1.55
86.01	8, 8	1.79	29.63	6, 10	1.23
85.89	2, 2	1.78	28.18	10, 15	1.00
83.09	10, 8	1.32	20.53	5, 8	1.29
80.92	2, 2	0.69	19.96	1+, 3	1.19
75.28	2, 2	1.24	11.88	4, 6	1.11
74.14	4, 3	1.46	03.88	6, 10	1.37
73.22	40, 50	1.45	2985.53	4, 6	0.75
69.81	4, 4	1.38	81.18	3, 5	(1.60)
60.24	4, 4	1.42	79.35	2, 4	1.29
50.62	10, 4	1.98	78.21	4, 6	1.55
47.72	6, 6	1.14	69.77	6, 10	0.56
42.32	3, 3	1.38	69.10	6, 10	1.58
41.26	20, 20	1.14	62.81	5, 10	1.05
36.75	3, 4	1.68	55.92	8, 12	1.11

The following 29 lines are apparently not separated. Most of them are, as the footnotes to the table indicate, probably of some other types, whose components have too small a separation and are too diffuse to permit of an analysis. The lines designated A are certainly not separated and those undesignated in column B are probably not separated. The lines designated (†) in remarks are very curious and probably identical. λ 5736.0, λ 4240.39, λ 3900.71 would form a series, but the next term about λ 3750 and the following terms are not present.

λ	*i*	B	λ	*i*	B
5508.5	8	D	4030.26	8	‡
5485.4	8		3989.27	2	n. i.
5136.0	10		00.71	15	¶
4851.8	6	*b* D	3781.80	8	‖ D
15.4	4	D	24.94	5	
4400.58	6	D*	06.79	5	D*w*
4273.80	12	†	3657.01	2	§
66.96	4		3549.90	5	
50.89	1+	D*w*	3431.71	8	†
40.59	20	A	3362.87	8	¶
13.45	5	A	3354.08	3	n. i. **
4181.13	8		3314.70	15	†
40.18	5	D somewhat	3131.23	1+	D*w*
28.08	12	A	3013.44	1+	††
4044.80	20	A			

* Possibly there is a weak pair of external components.

† *s*-component is a strong center with a broad background of diffusion on both sides; *p*-component wide.

‡ The *p*-component is broadened.

¶ Broad line for the *s*-component, sharp and strong on the edges and weak in the center; *p*-component sharp.

‖ The real components are probably overlapped by a carbon band line.

§ Possibly separated, but too weak.

** Not identified. It can scarcely be Exner and Haschek's line 3353.80.

†† Too weak and diffuse. It is possibly a doublet, but too far in violet for analysis.

VII. OSMIUM

λ	*i*	$\Delta\lambda/\lambda^2$	λ	*i*	$\Delta\lambda/\lambda^2$
4420.63	25	∓1.20 *s*	3882.03	7	∓1.65
	25	0.70 *p*	3794.05	4	1.29
4395.05	4	1.49	90.28	6	1.83
28.84	4	1.19	82.37	12	1.82
11.15	6	0.94	52.71	20	1.63
4294.17	8	1.18	3598.26	2+	(1.55)
		0.47	3561.04	8	1.35
61.01	20	1.95	59.96	4	1.58
12.02	12	1.72	28.76	5	1.61
4175.74	5	1.49	04.83	4	1.55
73.42	10	1.44	3402.03	3	1.50
35.95	15	1.97	3301.75	12	1.68
12.17	10	1.65	3268.09	6	1.61
4091.99	3	1.81	3262.44	4	1.37
66.90	8	1.54	3156.38	4	1.62
3977.38	6	1.54	3058.77	8	1.55
63.79	8	1.59	2909.19	10	1.40

Osmium was selected as a substance which, it was hoped, would give, with some types, repetitions throughout the spectrum, without having the confusion which arises from many lines of nearly the same separation. In this respect the substance was a disappointment. All the lines except one weak quadruplet are triplets and the separation of these varies from 0.70 to 1.97. There are a number of pairs of similar separation, but not enough representatives for a series. The spectral lines were never strong. Therefore, a long exposure in the magnetic field was required. A characteristic of the components is their great sharpness. The unrecorded *p*-components have very uniformly double the intensity of the *s*-components.

VIII. COMPARISON OF SUBSTANCES

It is desirable to compare the substances discussed above with lines whose separations give series. The two yttrium lines, λ 4395.91 and λ 3195.80, which are accurate duplicates such as one expects in series, are like six of the nine components of mercury, λ 5461 of the second adjacent series. The quadruplet λ 4167.65 is like four components of the barium sextet λ 5854. The quadruplet λ 3982.75 is like four components of the thirteen component mercury line λ 3663.5. The remaining components in these three lines are not absent because of weakness, since these lines are not weak lines. The two eleven component zircon lines have two pairs of components similar to two pairs of components in the nine component mercury line λ 5461. They have two other pairs of components represented in the barium principal series greater wave-length λ 4934. Their one remaining pair of components is found in barium principal series smaller wave-length λ 4554. That is, the components of these two lines are represented in three series types. There are other lines, both in yttrium and in zirconium, whose components can be selected by using more than one line of barium and mercury. Such a comparison points to a difference in the character of the lines rather than to an identity. From a glance at the tables it is seen that the components of lines are multiples of intervals; further, that the lines under comparison are likewise multiples of the same intervals, but that the multiples are only partially identical when they have the same interval, and the components have the same multiple proportions. One may further add, the components should have the same relative intensity. This is the condition fulfilled in the principal and subordinate series. The quadruplets of the principal series are 4 and 2 times the interval ±0.37 ($=\Delta\lambda/\lambda^2$), for field-strength 24,400, and the sextuplets 5, 3, and 1 times the the same values.

While I was engaged in making these comparisons an investigation bearing directly upon this point was published by Professor Runge.[1] I have accordingly tabulated the intervals from Professor Runge's contribution, intervals from his previous contributions, and the intervals in the present substances, all in one table which presents the matter more clearly than any verbal description. An interval multiplied by multiple "factors" (small whole numbers) constitutes a type by Preston's law. I have tried to find only representatives of Professor Runge's types, rather than all the lines and all the substances of these types. By way of explanation, the value "a" in the following table corresponds to the separation of 1.11 for present field-strength, and is the separation designated "normal triplet" by Professor Runge. This triplet gave him the value of 1.75×10^7 for e/m (charge/mass) in the equation, $a = \Delta\lambda/\lambda^2 = (e/m)\ (H/4\pi c)$, where c is the velocity of light and H the field-strength. With regard to these separations Professor Runge observes:

> Die bisher beobachteten komplizierten Zerlegungen von Spectrallinien im magnetischen Felde zeigen die folgende Eigentumlichkeit: Die Abstande der Komponenten von der Mitte sind vielfache eines aliquoten Teiles des normalen Abstandes "a" $= \Delta\lambda/\lambda^2 = (e/m)\ (H/4\pi c.)$ Sicher beobachtet sind bisher die Teile $a/2$, $a/3$, $a/4$, $a/5$, $a/6$, $a/7$, $a/11$, $a/12$.

In determining the intervals of the substances, I have used the components only of the line in question, and recorded the largest aliquot part of these components as the interval. This process yielded intervals which in themselves are multiples of a small value: e. g., there are intervals $a/11$, $2a/11$, $3a/11$, $4a/11$, $5a/11$, $6a/11$; $2a/12$, $3a/12$, $4a/12$, $6a/12$; $3a/16$, $6a/16$, $9a/16$, $12a/16$, and possibly others. These intervals may be expressed in $a/11$, $a/12$, $a/16$, and the multiple factors correspondingly increased. Professor Runge prefers this method. So far as the comparison of lines is concerned, it is entirely immaterial.

The actual number of intervals is many less than recorded in the tables. A bracket indicates that the intervals 0.53, 0.54, 0.55, and 0.57 may all in reality be the interval $a/2$(=0.554). The greatest

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[1] *Physikalische Zeitschrift*, 8, 232, 1907.

TABLE OF INTERVALS

Interval or Approx. Part of "*a*"	Multiples of Intervals="Factors"	No. of Lines Represented	Substance to Which Types Belong	Remarks	λ
	22, 15, 12, 7	1	*Zr*		3459.1
	22, 16, 10, 9	1	*Zr*		4440.8
	13, 7	1	*Zr*		3891.61
0.10	15, 13, 11, 2, 0	1	*Ne*		
(*a*/11)	20, 16, 14, 12, 8, 8, 4	1	*Hg*	¶ 1, N.II.	3655.
	12, 7	1	*Os*		4420.63
0.12, *a*/9†	7, 4	1	*Yt*		5510.1
	7, 5, 4, 3, 2	1	*Yt*		4235.89
a/6 0.18 0.185	10, 9, 8, 7, 6, 2, 1, 0	1	*Ne*		
0.19	14, 9, 5, 4, 0	1	*Ne*		
	9, 7, 5, 2, 0	1	*Yt*		4398.21
0.20	9, 6, 4, 3	1	*Yt*		4083.89
	7, 6	1	*Yt*		4682.5
(2*a*/11)	5, 1	1	*Yt*		4375.11
	5, 2	1	*Yt*		4177.68
	5, 4	1	*Zr*		4004.51
	10, 8, 7, 6, 4, 2	1	*Hg*		
0.21	3, 2	1	*Zr*		3674.98
0.22	9, 7, 3, 1	1	*Yt*		4236.10
	4, 3	1	*Zr*		3894.00
	4, 1	1	*Zr*		3916.16
(*a*/5)	8, 7, 6, 5, 2, 1	1	*Ne*		
	8, 5, 4, 3		*Qu. Ag. Al. Tl.*	I. N. S.	
	8, 5, 4, 3	1	*Ba*	I. N. S. *	
	8, 4		*Cu. Ra. Ag. Tl.*	I. N. S. *	
0.25	6, 5, 1, 0	1	*Zr*		4171.65
	6, 1	1	*Zr*	3*a*÷11 (5, 1)	4256.66
		1	*Zr*		
0.26 (2*a*/9)†	6, 5, 3, 0	1	*Zr*	*a*÷11 (15, 14, 8, 0)	4258.31
(3*a*/13)†	8, 3, 2	3	*Zr*	*a*÷11 (21, 8, ‖)	See *Zr* 6 Comp.
	7, 2, 0	1	*Zr*	*a*÷11 (18, 5, 0)	4061.70
a/4 0.265	8, 5, 3, 2, 0	1	*Yt*		3584.71
0.27	6, 5	1	*Zr*	*a*÷10 (16, 13)	3470.10
	6, 5, 4, 1, 0	1	*Ne*		
	7, 5, 4, 3	2	*Zr*	See *Zr* 8 Comp.	
	3, 2	1	*Zr*		4456.50
0.29	7, 1	2	*Zr*	λ 4003.28 and	3578.40
	2, 1	1	*Zr*		3588.15

TABLE OF INTERVALS—*Continued*

Interval or Approx. Part of "a"	Multiples of the Intervals = "Factors"	No. of Lines Represented	Substance to Which Types Belong	Remarks	λ
$3a/11$ 0.30	5, 2 (?)	1	*Ba*		5971.90
	4, 1	1	*Yt*		3833.10
	4, 1	1	*Zr*		3890.58
	4, 3	1	*Zr*		3568.32
0.305	6, 3, 2, 0	1	*Zr*	$a \div 11$ (18, 9, 7, 0)	4093.32
$3a/10$ 0.32	9, 4, 0	1	*Zr*		4187.30
	5, 2	1	*Zr*		4418.80
0.33	4, 2	1	*Zr*		4034.30
	4, 1	1	*Zr*		4031.57
	2, 1	1	*Zr*		3284.89
0.34	3, 2, 1	1	*Zr*		3396.51
	4, 1	1	*Zr*		3634.33
$a/3$ 0.36	5, 3, 1	1	*Zr*		3483.70
	3, 2, 2	1	*Zr*		3482.96
	5, 3, 1	2	*Ba*	H and 2 N. †	
	4, 2	2	*Ba*		
0.37	4, 2	1	*Yt*		3200.04
	3, 1, 0	1	*Zr*		3376.42
	6, 4, 3, 2, 1, 0	2	*Zr*	See *Zr* 11 Comp.	
0.38	5, 3	1	*Zr*		3323.21
	5, 1, 0	1	*Yt*		4477.10
	4, 1, 0	1	*Yt*		3951.76
0.39	4, 3, 2	1	*Zr*		4110.29
	4, 3	1	*Zr*		3434.08
($4a/11$)	4, 3, 2, 1, (0?)	8	*Hg*	I. N. II. *h.*	3125.80
$3a/8$ 0.42	3, 2	8	*Zr*		
	3, 1	6	*Zr*	See Zirconium Quadruplet Table	
	4, 1	3	*Zr*		
	4, 2	2	*Zr*		
	2, 1	1	*Zr*		
0.43	5, 4, 2, 1, 0	2	*Zr*	See *Zr* 9 Comp.	
	4, 3, 2, 0	1	*Zr*		3368.01
	6, 4, 1	1	*Zr*	$a \div 10$ (27, 17, 4)	3554.31
	4, 3, 2, 2, 1, 1	1	*Yt*		3818.49
0.48	3, 1, 0	1	*Zr*		5350.50
$5a/11$ 0.50	5, 6, (1?)	1	*Zr*		3498.00
	3, 1	3	*Zr*	See *Zr* 4 Comp.	
	3, 2, 1, 1, 0	1	*Yt*		3950.51
	3, 1	2	*Yt*	See *Y* Quadruplet	
0.51	2, 1	1	*Zr*		4582.50
	3, 1	2	*Zr*	λ 4429.28 and	4024.20
	3, 2, (?)	1	*Zr*		3480.59

TABLE OF INTERVALS—*Continued*

Interval or Approx. Part of "a"		Multiples of the Intervals = 'Factors'	No. of Lines Represented	Substance to Which Types Belong	Remarks	λ
	0.53	2, 1, 1, 0	1	*Zr*		4055.20
	0.54	5, 3, 2, 1, 0	1	*Yt*	I. N. I. S.	4199.46
		4, 2, 2, 0, 0	1	*Zr*		4268.22
	0.55	3, 2, 1	1	*Ba*		
		3, 2, 1	2	*Yt*	λ 4358.91 and	3195.80
$a/2$		2, 1	1	*Yt*		
		3, 2, 1	1	*Zr*		4590.81
		5, 3, 2	1	*Zr*		4431.70
		4, 3, 2, 1, 0	1	*Ne*		
		5, 3, 2, 1, 0		*Hg*	I. N. I. S.	
		5, 2, 1, 0		*Hg*	I. N. II. S.	
		4, 3, 2, 1		*Hg*	2 N. I.	
		4, 3, 1		*Hg*	2 N. II.	
		4		*Hg*	2 N. III.	
	0.57	2, 1	2	*Zr*	λ 3934.99 and	3973.68
	0.60	3, 2, 2, 0	1	*Zr*		4214.05
$6a/11$		1, 2	1	*Zr*	‡	3454.71
	0.63	3, 2, 1, 1, 0	1	*Yt*		3628.89
($3a/5$)	0.67	3, 1, 0	1	*Zr*	a 11 (20, 7, 0)	3501.50
($3a/4$)	0.83	2, 1, 0	1	*Zr*		4046.30

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* *Ba* λ 4166 is just as accurately represented by a 4 (6, 4, 3, 2) and *Ra* λ 4436, by a 4 (6, 3). Neither of the two systems represents it accurately. Multiples of (a 11) represent these lines even better, except for one component.

† Series types, shown by *Na*, *Cu*, *Ag*, *Al*, *Pt*, *Mg*, *Ca*, *Sr*, *Ba*.

‡ The p-component lies outside of the s-component.

¶ When p- and s-components are duplicates in position, they are designated by repeating a number. The triplets of this first adjacent series are 3 and 5 times a 5.

deviation, 0.09, is in a fourfold of 0.53. It is advantageous, however, to preserve the factor 0.53 in the tables just as it is. For, if a sixfold or greater factor of 0.53 should be found in any substance, the interval would probably not belong in $a/2$. When the multiple factors are small, wider ranges in the intervals can be regarded as coming under one interval. The inverse is true for large multiple proportions. Therefore one could more readily classify 0.33 (with largest factor equal to 4) under 0.32 (with largest factor 9) than in the inverse manner. However, 0.33 is an aliquot ($3a/10$) of a. Taking $3a/10$ as an interval, the 0.34 (with factor 4) interval is reasonably near it but the 0.32 interval is near the limit of allowable error. The interval 0.29 is midway between $a/4$ (=0.28) and $3a/11$ (=0.30.) Without material error, it could be classified $a/4$ or $3a/11$. Its factors are not present in either $a/4$ or $3a/11$ and for the present may remain unclassed. The same difficulty arose with 0.21 until further classifying showed the presence of 2, 3, and 4 times 0.21 and that these could be represented by $3a/16$, $6a/16$, $9a/16$, and $12a/16$.

It may be contended that the magnitude of the intervals indicates an irrational part of the normal "a" rather than aliquot parts of such a normal value, or in other words that the "normal" is fictitious. Such a conclusion is possible and if an examination of other substances gives other apparent irrational intervals with numerous and large factors, it will be the more logical conclusion. As soon, however, as one omits the quadruplets, there remain but few lines which suggest this difficulty. With respect to the quadruplets one can very frequently change the interval and at the same time change the factors so that the line is practically just as well represented. Also, with two values, i. e., four components, distinction is difficult, whereas with six and more components the intervals can be determined with considerable sharpness.

Lines with many components have frequently a larger interval which occurs as a common difference in passing from component to component, instead of measuring from the position of the undisturbed component. In neon one finds the *s*-components of λ 6217.5 represented by $\pm(14, 9, 5)\ a/6$, or a common difference of $5a/6$ repeated four times. The *p*-components of the same line are represented by $\pm(5, 0)\ a/6$, or $5a/6$ repeated twice more. In zirconium 3459.1 the *s*-components are $\pm(23, 15, 7)\ a/11$ or the distance $8a/11$ occurs four times. For the *p*-components of this line one finds $12a/11$ twice repeated. In yttrium λ 4235.89 the perpendicular components are represented by $\pm(7, 5, 3)\ a/6$, and the parallel components by $(4, 2)\ a/6$ or the distance $a/3$ is measured eight times in this line. Numerous other cases can be found in the table.

From the examples given one sees that the distance between the adjacent *p*- and *s*-components is much smaller than the distance between the single *p*- or single *s*-components. This smaller distance is naturally more accurately determinable as the number of components increases. Then it is evident that the greater separations are always whole multiples of small distances, and also that the distances from the position of the undisturbed component are whole multiples of such a small distance, or "interval."

In the quadruplets, the small interval is more difficult to determine, and they, therefore, have less weight in determining this fundamental question of the rationality or irrationality of the "interval" space. In these quadruplets, however, one sees that the components stand in a simple numerical relation to each other.

The multiples and their intervals remind one of the law of multiple proportions in chemistry.

By means of intervals, their multiples and multiple factors, one obtains a most convenient method of comparing lines and substances. The quadruplet principal series types, which Professor Runge found in *Na*, *Cu*, *Ag*, *Al*, *Tl*, *Mg*, *Ca*, *Sr*, are represented by $a/3$ (4, 2).

In yttrium there is one line, λ 3200.44, which may possess these values but the companion sextuplet is absent. It may be of type (15, 7) $a/11$. The sextuplet principal series, $a/3$ (5, 3, 1), found in the same substances has a solitary representative in zirconium in the line λ 3483.70, but the companion quadruplet is absent. *Hg* first adjacent series satellite λ 3663.05 is probably represented in yttrium by λ 4199.46. The separations of the components of the yttrium line are a trifle smaller. One line, λ 3624.10, in zirconium is like two lines, λ 4128.49 and λ 3930.84, in yttrium. These lines are 4 and 1 times $3a/11$. Similarly there are five lines in zirconium whose separation is like two yttrium lines and the separations $5a/11$ (3, 1). Among these there is considerable variation from the desired accuracy. These lines are zirconium λ 4429.3, λ 4199.2, λ 4043.8, λ 4024.2, λ 3296.6, and yttrium λ 4475.9 and λ 3449. Zirconium λ 4590.8, barium λ 5997.4, and yttrium λ 3195.8, λ 4358.9 are types of $a/2$ (3, 2, 1). These yttrium lines are the best duplications observed. The most prominent feature of the interval tables is the types (interval times factors) which are only once represented. As before mentioned, it requires four lines to make sure of a series. Hence the table excludes series except in zirconium under the interval 0.42. These lines are unequally distributed in distances (in terms of vibrations per cm).

The intensities are also irregular. The factors, by which the intervals must be multiplied to give the required separation, are very numerous, as well as possessing a variety of combinations. The principal series and second adjacent series of the previously mentioned substances have the interval $a/3$. This interval is represented by eleven lines in yttrium and zirconium, but only in two cases are the factors of proper magnitude and number to produce the series type. This leaves nine new types under this interval.

Under $a/11$, an interval of the *Hg* first adjacent series, and multiples of $a/11$, there are six yttrium, fifteen zirconium, one neon, and one osmium lines, or a total of twenty-three lines. There are some duplicates, which leaves eighteen types, including neon, and these are all different from the type of *Hg* line λ 3665. The interval $a/5$ is well represented in the first adjacent series satellite of *Cu, Hg*, *Al*, and *Tl*, but the interval does not enter in right proportions in yttrium or zirconium to form the same types. Some types have the same factors as others with one or more factors suppressed. The question naturally arises, whether these lines may not be duplicates and whether the omission might not have arisen from weakness of the component or inadequate exposure. This may be true in a few cases, but generally it is not for the following reason: The ratio of the intensity of components is known both in the line having all the components and in the line having some components hypothetically missing. A simple mental calculation will then tell whether the missing component, if existing at all, may have been too weak to leave a photographic impression on the plate.

IX. CONCLUSIONS

1. The lines of the triplet class in barium mostly fall into groups with a separation similar to the separation of some components of lines other than triplets.

2. A great majority of all lines, having more than three components, possess underlying simplicity and likeness in the great variety of their separations. This simplicity or similarity is manifested in small magnitudes which are designated by the term "intervals." The components of these lines are obtained by multiplying the intervals by "factors." The intervals themselves may have mul-

tiples. The smallest intervals are aliquot parts of a (where a is the separation of the "normal triplet" as given by Professor Runge). The latter recently found in neon the aliquot intervals $a/2$, $a/3$, $a/4$, $a/5$, $a/6$, $a/7$, $a/11$, $a/12$. All, except $a/12$, are observed in the present experiment.

3. The great variety in the magnetic separations arises principally from the variation both in number and in magnitude of the interval factors. The product of interval and factor or combination of factors gives the types of separation.

4. The interval 0.37 $(=a/3)$ times (4, 2) and (5, 3, 1) gives respectively the quadruplet and sextuplet principal series and second adjacent series found by Professor Runge in *Na, Cu, Ag, Al, Tl, Mg, Ca, Sr, Ba, Ra*. The quadruplet has one doubtful representative in yttrium, and the sextet one line in zirconium. However, the same interval combined with factors in other proportions gives nine new types. One of the *Hg* first adjacent series types has a solitary representative in these substances, but the intervals yield at least 18 new types.

5. The substances yttrium and zirconium yield a great number of new types.

6. The most prominent characteristic of the numerous new types is the number which are unrepeated in the spectral range of these experiments. It would be interesting to extend the measurements far into the ultra-violet with a much stronger field to see whether there are not more repetitions and even series.

7. The interval (0.42 $[=6a/16]$) in zirconium is the only one which would promise series types. There are eight quadruplets of one type and six of another, but no series found.

8. There are six lines in yttrium like seven lines in zirconium and these are represented by three types. This is scarcely enough terms to suggest similarity of the substances. Chemically, however, there is a similarity. The substances are parallel terms in two adjacent (third and fourth) Mendelejeff's groups.

9. The one quadruplet of osmium has an interval of the first adjacent series, but it is not of the latter type.

10. An investigation of triplets for series is always tedious. Dividing them into groups, as in barium above, is advantageous frequently. They then look like other types with suppressed components. But

in yttrium and zirconium one would be at a loss to know which type had the component suppressed. This would suggest that a given separation in such triplets may represent more than one type. The investigation of yttrium triplets for series has been reasonably complete and negative. In zirconium, time has permitted the study of only a few triplet magnitudes. The results have been likewise negative. The triplet values are extended over a large range. They do not collect around a "normal separation" or multiples of aliquot parts of a normal separation.

11. Lines with no components (unseparated) in zirconium show no series. Most of these lines are probably unanalyzed types.

12. There are a great many lines which may be associated in pairs. Such lines are comparatively near each other on the scale of vibrations. The pairs may have the same separation or not, and have the same or a different number of components. In substances which have yielded series, such pairs are frequently conspicuous. These pairs repeat themselves in other parts of the spectrum with considerable uniformity of separation. In osmium repetitions are not present, and in yttrium and zircon only apparently so since the separations of the prospective pairs are very irregular.

X. GENERAL CONCLUSION

There is a general dissimilarity between the lines of yttrium and zirconium; and between these lines and the lines of all substances which have yielded series. But all substances have common fundamental intervals of small magnitude, and few in number, intimately connected with a "normal separation."

In conclusion I wish to thank Professor Voight of the University of Göttingen, Germany, who suggested this investigation and kindly placed the resources of the Institute at my disposal, for his friendly assistance, and enthusiastic encouragement. Likewise I acknowledge my obligations to Professor Runge of the same university, whose invaluable experience in spectral work was courteously given to me.

Brace Laboratory of Physics
University of Nebraska
December 1907

ON THE SENSITIVENESS OF PHOTOGRAPHIC PLATES AT DIFFERENT TEMPERATURES

By ROBERT JAMES WALLACE

In 1895 Abney investigated the effect of temperature upon the sensitiveness of photographic plates, and gave his conclusions in an address before the Royal Photographic Society.[1] His methods and results may briefly be summarized as follows: a special box constructed so that its temperature could be varied by means of a freezing mixture or a "heated brick" contained the plate under test. When at the determined temperature, exposure was made through a square aperture, moving along a slot in the lid, to a small Argand paraffin, or amyl acetate lamp. From measurement of the plates thus obtained, where the light was constant and the exposure varied, this investigator found that there was "not necessarily any variance in the gradation of the curves—but that the rapidity is altered—although not to the same degree, for each kind of plate," being invariably less as the temperature is reduced. With constant exposure to light of varying intensity, he also found that with exposures made above 33° C. the gradation changed, the curve becoming steeper, although up to this temperature the heat had no other effect upon the plate beyond making it more rapid. In this latter portion of the work, the light used was not exactly the same in the hot and cold experiments, exact values not being aimed for, but merely the change in gradation.

Later, E. S. King, of Harvard College Observatory, also made some experiments upon the influence of temperature upon sensitiveness,[2] and exposed two portions, cut from the same plate, to temperatures of "about 0°," and "about 80°," obtained by placing one out doors, and the other over a hot-air "register" until the plates had taken the temperature of their surrounding air. They were then exposed for one minute to the extra-focal image of *Polaris* in the telescope. In the case of the cold plate the "focus was set to reduce

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[1] *Action of Light in Photography*, Sampson Low, Marston & Co., London, 1897.

[2] "Photographic Photometry," *Photo-Beacon*, **17**, 267, 1905.

the light by one-half magnitude." It was found on development that the images were of similar density, showing that "the difference in sensitiveness for a change of about 70° or 80° is 0.5 magnitudes, the cold plate being the more sensitive." From further experiments it "was found that temperature not only affected the sensitiveness of the plate but also changed the gradation of the intensities of darkening."

When the results of these investigators are compared they are almost directly opposed to each other. The work presented in this paper was therefore undertaken in the hope that a greater concordance might be obtained by working under definite conditions.

METHOD

The plan of work will first be noticed, as it will assist in the clear understanding of the results. Plates were exposed in a temperature-box constructed for this purpose, somewhat similar to that used by Abney, at temperatures varying from +100° to −14° C., and were developed and fixed under precisely similar conditions. Another series of exposures under natural conditions of temperature, and varying from +24° to −14° C. was made to corroborate the laboratory results with artificial temperatures. The negatives thus obtained were measured with the spectro-photometer especially constructed for such work, and detailed in a former paper,[1] and curves were plotted showing the relation between exposure and density for each variation in temperature.

TEMPERATURE-BOX

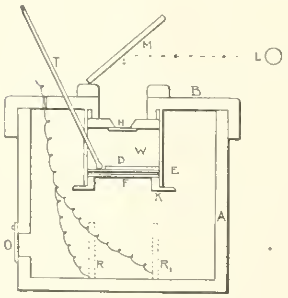

FIG. I

The design of the temperature-box will be understood by reference to the plan which is given herewith (Fig. 1): *A* is a zinc-lined box about 12 inches square, closed by the light-tight lid *B*, which carries with it the cubical plate-chamber *W*. This chamber contains a transparent scale-plate *D*, which rests in contact with the surface of the sensitive plate *E* under test. This sensitive plate is

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[1] *Astrophysical Journal*, 25, 124, 1907.

held in position by means of a light wooden frame *K*, in which is fitted a piece of deep-ruby glass *F* to avoid action from scattered light inside the box *A*. Light is obtained from an acetylene burner at *L*, and reflected down by means of the mirror *M*, through the ground-glass *H*, and thence passes to the sensitive plate. A thermometer *T* is inserted so that its bulb rests in contact with, and presses against, the sensitive surface. Increase in temperature is obtained by leading the 110-volt direct current through the two resistance coils *RR′*, which run the entire length of the box. For reduction in temperature many experiments were made with various freezing mixtures, and also with ether spray and liquid air, which were introduced at *O*.

The scale-plate used was a negative strip developed from an exposure to the revolving sector-disk machine. The method of exposing through a transparency was selected as being most desirable, as by this means there is obtained a constant exposure to light of variable intensity, thus duplicating the conditions under which one works in the case of exposure at the telescope, or in general camera work. The dimensions of the transparent portions of this scale-plate measure 6.5×2.7 cm, while the plates used were 8×10 cm. The use of the sector-disk machine itself would have been still better, but the impossibility of making use of it without practically rebuilding it, led to the abandonment of the idea.

LIGHT

The light used was acetylene, prepared in a Colt generator of water-to-carbide type, and burning from a ½-ft. Halm burner, under a uniform pressure of 2⅝ inches of water. In front of the flame, and separated from it by a distance of 11 mm, a metal plate is supported from a cylindrical metal chimney, this plate being pierced with a circular aperture of 2.5 mm diameter. This aperture is at such a height that its position comes immediately in front of the center of the white portion of the flame. The burner is fed with gas which passes from the generator, and then through a large bottle containing KOH; a manometer indicates the pressure.

If (as has been pointed out by previous writers) care be taken not to turn down the flame at the burner, but to cut off the gas supply abruptly, this arrangement forms an exceedingly good intensity standard, in cases where the spectral quality is suitable. In the present work no compensation color-filter was made use of, as the spectral distribution of the light intensity was of no moment, and was used with similar plates throughout. Generators of the carbide-to-water type are unsuited unless equipped with some form of pressure governor.

PLATE, EXPOSURE, DEVELOPMENT, AND PRECAUTIONARY MEASURES

As the primary object of the investigation was its relation to the photography of faint celestial objects, only one make of plate was experimented upon, viz., "Seed 27 Gilt Edge," which was selected because of its uniformly greater speed.[1] The exposures were made by first dividing them into three groups according to the temperatures, as follows:

A. From +24° C. to +100° C. } (Laboratory exposures)
B. From +24° C. to −14° C. }
C. From +24° C. to −14° C. (Outdoor natural temperature exposures)

In the actual handling of both groups A and B, separate sets of plates, all of similar emulsion number, were exposed at each of the following temperatures: (A) +24°, 50°, 75°, 85°, 90°, 95.5°, and 100° C., and (B) +24°, 10°, −2°, and −10°. Besides, several 8×10 plates were cut into six pieces, and the resultant smaller sizes were exposed similarly, care being taken that each plate of the sets of six was exposed at a different temperature, thus assuring direct comparison with each other.

The exposure given each plate was carefully kept constant in all save the actual temperature of the plate itself. The distance of the flame-diaphragm from the center of the mirror *M* was 36 inches, and the duration of exposure was 3 minutes, accurately timed by means of a stop-watch.

During exposure of any one group, the plates were removed from the temperature-box, numbered, and laid face up in an empty plate-

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[1] Since the above was written Messrs. Lumière have introduced a special "Σ" emulsion, which from measurements by the writer give a speed increase of 2.3 times that of the Seed "27." This Σ plate, however, cannot be used *generally* in astronomical work, as the grain is 1.7 times larger than that of the "27." The Σ plate also fogs badly in development.

box for a few minutes, until they had assumed the temperature of the room, and then replaced in their original box until all of the units of that group were completed.

Each set of plates was developed at the same time, the reducing agent being Rodinal, which was used at a dilution of 1:24; the temperature of development was 20° C., and the length of time 3 minutes. Some few of the sets were purposely developed for a shorter time—down to 1 minute 30 seconds—in order to make certain that a difference in γ would not affect the general result. In every case the plates were first soaked, immediately before development, in a large quantity of distilled water (temp. 20°) in order to insure the certainty of equal temperature for each plate.

In the case of the plates exposed at reduced temperatures, by the aid of freezing mixtures of ice and salt, etc., the exposure of the plate for some time in the box, to enable it to assume the necessary temperature, gave rise to the idea that the presence of so much aqueous vapor might give disturbing results, even although the plate itself, by reason of its position in the inner chamber, seemed to be protected therefrom. However, the action of water vapor was investigated in the following manner: A $3\frac{1}{4}\times4\frac{1}{4}$ plate was cut into two strips, one of which was soaked in distilled water for 3 minutes, and then removed, drained, and placed in the plate-holder side by side with the dry slip, and both were immediately subjected to simultaneous exposure. Both plates were then soaked in water and developed.

Examination during development shows that the image appears with equal rapidity on both strips, but as development progresses the "dry" strip becomes apparently more dense. Examination of the fixed and dried negatives confirms this greater density. Measurement of the plates furnishes data for the construction of the accompanying curves (Fig. 2) from which it will be seen that the general speed is reduced by $2^{0.5}=1.4$ times; the curves, however, do not cross, but appear to be shifted along the log E axis and parallel to it. From the temperature-curves, which will be shown presently, it will be seen that aqueous vapor (if present) therefore does not alter the result. This experiment was several times repeated, for varying times of preliminary immersion, with uniform results.

Any disturbing influence of the ether vapor upon the sensitiveness was also investigated, but with negative results: even bathing in sulphuric ether appears to have no effect upon either D or γ_∞.

In the course of the work it was also necessary to determine the influence of soaking in water prior to development, as some of the test plates were developed without this initial soaking. Experiments upon a sector-disk exposure, where the plate was cut in half before development, and one portion soaked in water, showed, when both parts were developed together, that the image appears first upon the dry half and seems to have greater vigor. As development progresses, the wetted plate rapidly overtakes the other and (by ruby light) soon no difference is discernible. Measurement of the plates, however,

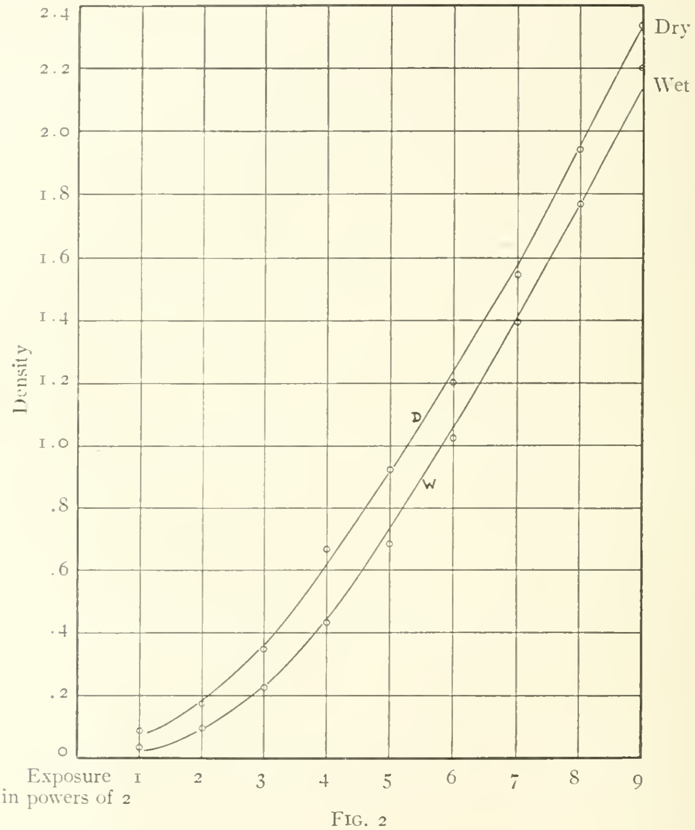

FIG. 2

confirms the results arrived at by Mees and Sheppard, viz., the wetted plate has a higher γ, and is likewise shifted along the log E axis,[1] but this does not influence the temperature test results.

Fourteen duplicate sets of plates completed the laboratory experiments, of which eight sets were of Group A. Preconceived opinions held by various observers regarding the influence of temperature upon sensitiveness necessitated verification of the laboratory results by exposures made at duplicate temperatures under natural conditions. For exact quantitative work exposure at the telescope on "extra-focal" images could not be considered, as uniformity of photographic light intensity is impossible; for, while an experienced observer is able to detect a certain amount of atmospheric "thickening," yet he cannot make any reliable measure of the same, nor can he say what absorbing influences are present at any time during the work, particularly in the more refrangible wave-lengths, the region of greatest photographic activity.

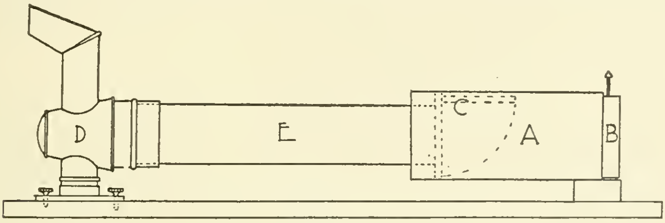

FIG. 3

For this reason, therefore, a separate arrangement was made which is shown in outline in Fig. 3. *A* is a rectangular wooden box into which fits the plate-holder *B*, while a flap-shutter, *C*, controls the length of exposure. Light is supplied from the constant acetylene burner at *D* (this burner being the same as was used for the laboratory tests). The light was used at a constant distance of one meter from the plate surface, and fits "light-tight" into the end of the brass tube *E*.

In practice the scale-plate (which was the same as used in the foregoing experiments) was placed in contact with the sensitive plate in the plate-holder. The entire apparatus and the plates intended for use were placed out-doors in the open air some hours prior to

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[1] *Journal of the Royal Photographic Society*, 47, 88, 1907.

their exposure, and arrangements were also made for changing plates out-doors. As a rule, six exposures were made out-doors at low temperature, followed by six exposures in the laboratory at "normal" temperature. Altogether, Group C covered eleven sets of plates, averaging four to eight plates to a set. As with Groups A and B, each set of Group C was developed at one time, under constant conditions as previously described.

The laboratory experiments connected with this work were begun in the early part of 1906, but the natural temperature verifications could, of course, be performed only during the winter months, and were conducted at various times during 1906–7 and 1907–8. These past two seasons have not been characterized (at this location) by very low temperatures, but sufficient data have been obtained to give almost uniformly concordant results.

METHOD OF RECORDING RESULTS

When all of the principal plates had been measured in the photometer, the densities for each of the plates corresponding to similar temperatures were combined, and a mean was obtained. This tabulation showed a good agreement between each of the plates, there being no error greater than that which could be ascribed to the local variations of the plate coating. It is not necessary that these results be given *in extenso*, but Table I gives an example which may serve well as a specimen.

TABLE I

Plate	Measured Density of the Corresponding Strips								
	1	2	3	4	5	6	7	8	9
A......	0.0719	0.3642	0.8632	1.3019	1.6441	1.8064	2.1117	2.4012	2.5312
B......	.0691	.3819	.8679	1.2729	1.5262	1.8756	2.1149	2.2921	2.4160
C......	.0712	.3687	.8855	1.2100	1.5037	1.8621	2.0980	2.2115	2.4322
Mean ..	0.0707	0.3716	0.8722	1.2616	1.5580	1.8480	2.1082	2.3016	2.4598

The mean densities thus obtained, when plotted on squared paper, with the density as ordinates, and the abscissae as exposures, give the sensitiveness-curves for the temperatures considered. Fig. 4 shows the curves of temperatures +24° to 100° C., while Fig. 5 shows the effect of reduction from +20° to −20° C.

RESULTS

In these curves representing temperature increase, it will be noted that between the temperatures of 24° and 75° the curves cross one another: this is the "alteration in gradation" spoken of by both Abney and King. In the opinion of the writer it is this "alteration" which accounts for the discordance between the findings of these workers. According to Abney, *increase* in temperature results in added speed, while according to King, greater speed, even to 50 per cent., is obtained by a *decrease* in temperature. In reality

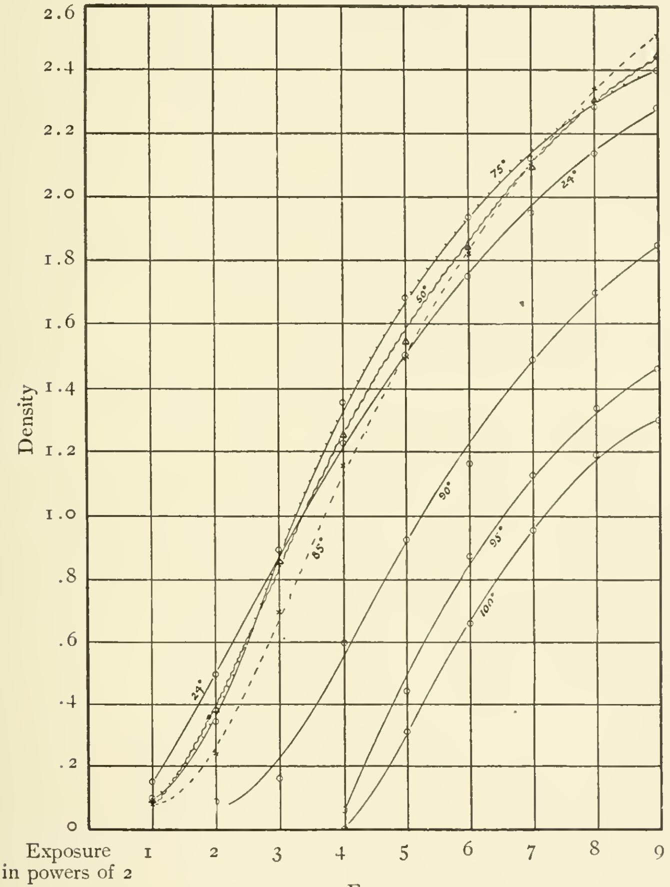

Fig. 4

then, it simply depends upon which portion of the curve is taken as to whether the speed is increased or reduced, i. e., whether one considers faint objects with consequent low photographic densities, or bright objects with full exposure and consequent high densities.

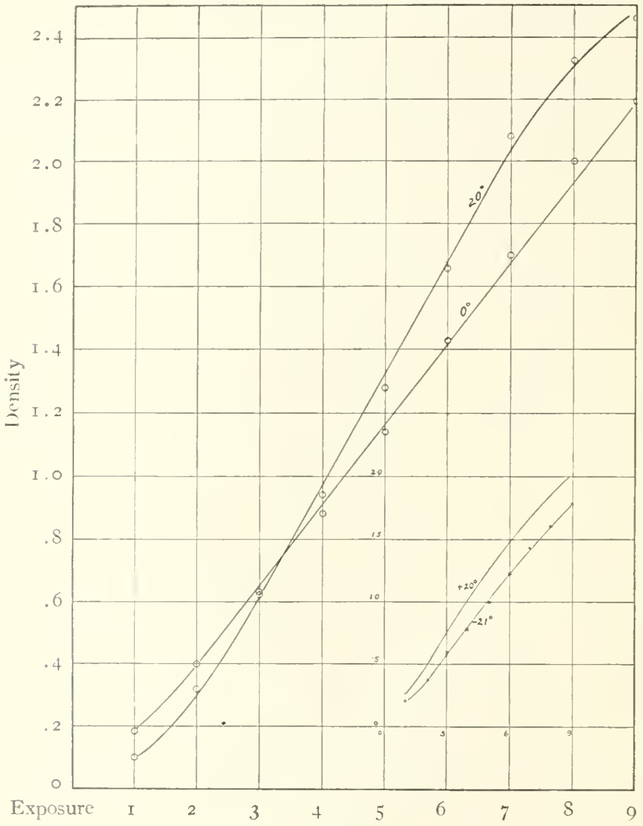

FIG. 5

In the negatives obtained, the development was such that the "straight portion" of the characteristic curve embraced about five magnitudes. As the densities of a photographic negative throughout this "straight portion" are proportional to the logarithm of the light received, then it is sufficient to multiply D by 2.5 in order to convert it into stellar magnitudes. Such magnitudes, however, will not be absolute, but merely relative, as they are based upon the light used in the course of the investigation, and will vary according to the initial intensity, for, as is well known, the photographic plate does not follow a straight-line law with reference to intensity.

Thus, from this point, where the curves cross, the plate becomes slower for fainter stars as the temperature is increased, while under the same conditions the plate is faster for the brighter stars. Beyond a temperature of 85° C. the plate breaks down, and a considerable amount of fog is induced,[1] which increases very rapidly with a further slight rise, until at 100° C. it is very heavily veiled and badly mottled. Measurement of the plates taken at this temperature presented considerable difficulty. The actual "fog value" of each plate was, of course, subtracted from the densities before plotting.

Taking the case of the curves representing the plate values for the temperatures of 24° and 50°, we see from the mean separation of the curves $D_{0.4}=0.06$, which amounts to 1.04 times less chemical light action on the heated plate than on that at normal temperature, for the fainter stars; while on the other hand, for $D_{2.2}=0.95$, the action is increased 1.9 times. Between 24° and 100° the mean difference is $2^{3.5}$, or 11.3 times general reduction in speed.

The original scale-plate and the negatives therefrom, possess nine separate shades or tone-values, and defining them from the weakest to the most opaque as $D_1, D_2, \cdots\cdots D_9$, we may carry the method of recording results a step farther and re-plot each in terms of D_n and temperature, and thus afford a rapid connection to everyday routine work. Such a series of curves is shown in Fig. 6.

In the preparation of this figure, all of the curves from "normal" (+24° C.) to +100° C. were first plotted and then all of the values of D for temperatures lower than +24° were reduced to a mean D for each point, and shifted vertically to connect. As has already been stated, the magnitude value of the change in D_n with temperature cannot be referred to an absolute scale, because in quantitative photographic astronomical work, the value of the intensity recorded is dependent upon (*a*) the atmospheric absorption, tremor, etc., and (*b*) the length of exposure. Care with reference to the development

[1] Accompanied by reversal in the lower values of D.

constants eliminates these (relatively) so that to consider the star image in terms of D_n it simply remains to read off the corrections necessary for temperature.

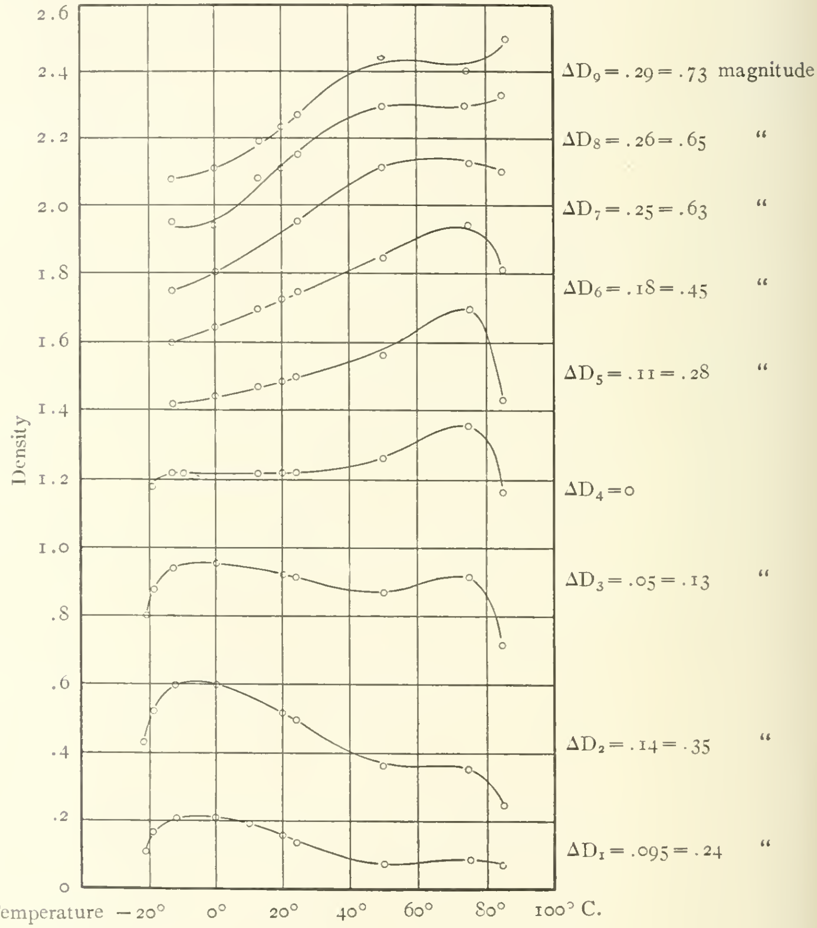

Fig. 6

Broadly considered, it may be stated that for images at about the minimum of photographic action, the sensitive plate is faster by about 0.35 magnitude in a temperature range of from –18° to +32° C. (0° to +90° F.) and for the high values of D (corresponding to the brighter stars) about 0.7 magnitude slower, while for stars of medium density (corresponding to a value of about $D=1.2$) there is no apparent change.

From the examination of the measurements and curves of this entire series of plates, the writer is forced to the conclusion that there is a limited range of temperature at which this added D value for light of low intensity is apparent, and that at other temperatures, either above or below this region, the sensitiveness-curve falls rapidly and smoothly. In other words, photographic sensitiveness plotted against temperature may be represented by a curve similar to the probability curve. This idea is borne out when we consider the curves already shown, where, in the higher temperatures, there is a certain point above which the plate curves fall off from the normal and are moved bodily along the log E axis; precisely the same effect is indicated in the case of temperature reduction curves representing successively lower temperatures. This is to be expected when consideration is given to the classic experiments of Dewar, who showed that there was a very great decrease in sensitiveness at temperatures about $-200°$ C. The influence of temperature upon general velocity reactions would also point to a similar conclusion.

The points dealt with in this work require extension with special apparatus, by (preferably) other investigators, at temperatures intermediate to $-10°$ C. and $-200°$ C., as it would be desirable to acquire data relative to the formation of the rising branch of the curve. It should also be pointed out that it by no means follows that the region of maximum is identical on plates of different chemical constitutions, or that difference in wave-length may not modify the conclusions arrived at.

YERKES OBSERVATORY
April 28, 1908

THE RELATION OF LIGHT OF VERY SHORT WAVE-LENGTH TO SOME VACUUM TUBE PHENOMENA

By THEODORE LYMAN

Schumann has observed that the radiation which comes from the neighborhood of the cathode in a vacuum tube is particularly rich in light of very short wave-length. The writer began the present investigation for the purpose of ascertaining if these most refrangible rays were confined entirely to the region near the negative electrode. Such an inquiry is of some interest for two reasons. First, from the practical standpoint, it is important to know the distribution of light within a vacuum tube in order that the tube may be given the best shape for the purposes of spectrum analysis. Second, from the theoretical standpoint, it is important to ascertain the relation of the sources of light of short wave-length within the tube to the points of luminosity, because of the bearing of this relation on the theory of electric conduction and radiation in gases at low pressures. The first few pages of the paper are taken up by a description of experiments on this subject.

The latter half of the paper relates to the part played by light of very short wave-length in producing ionization within a discharge tube. That some kind of radiation acts to increase the conductivity in the electric discharge at low pressures has been proved by J. J. Thomson; and the effect has been attributed by him to the influence of the *Entladungsstrahlen* discovered by Wiedemann. One of the objects of the present paper is to show that in all probability the active agent in producing ionization is not a new form of radiation but light of wave-length shorter than λ 1800. The argument is based on the recent work of Mr. Frederic Palmer and upon the writer's observations on the relative efficiency of various sources in producing the most refrangible rays. The subject naturally leads to an inquiry into the nature of *Entladungsstrahlen* themselves, and the last part of the paper will be found to contain some suggestions on this question.

In attacking the problem of the distribution of light in a vacuum tube the ozone-producing action of the most refrangible rays has been employed. It has recently been shown[1] that in the neighborhood of λ 1800 this action increases very rapidly with decrease in wave-length, to such an extent in fact that the discoloration of potassium iodide starch paper forms a good test for the presence of the most refrangible rays. The shape of the discharge tube employed in the present experiments was suggested by an apparatus used by H. A. Wilson[2] in an investigation on a different subject. Two circular aluminum electrodes, 2.3 cm in diameter and 14.5 cm apart, were joined together by a light glass frame and were connected to the terminals of a tube, 52 cm long and 3.5 cm in diameter, by coils of wire. A bit of soft iron at *A* (Fig. 1) permitted these electrodes to be moved to any position in the containing vessel by the use of an electromagnet external to the apparatus. A piece of capillary glass tube *B*, 2.5 mm in bore and 4 cm long, served as a diaphragm through which the light under investigation must pass before reaching the test paper. As the writer has pointed out, it is necessary that this paper be in close contact with the fluorite window *C*, for it if be removed to the distance of even one mm, the absorption of the air for the light of short wave-length is sufficient to reduce the ozonizing action to such an extent that the paper will not respond to it in a reasonable time. The tube was excited by a section of a storage battery giving a difference of potential of 1700 volts; the current, which was controlled by a suitable external resistance, was read by a Weston ammeter, the potential difference was determined by a Braun's electrostatic voltmeter.

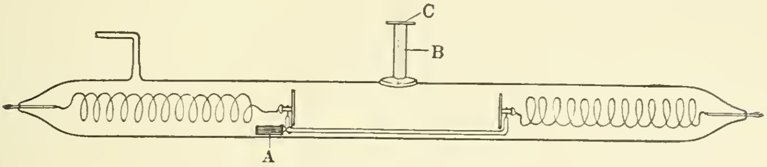

FIG. 1

Hydrogen is known to give a strong spectrum in the region discovered by Schumann. The first experiments were accordingly made

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[1] *Astrophysical Journal*, 27, 87, 1908.

[2] Thomson, *Conduction of Electricity through Gases*, p. 530.

with this gas. The exhaustion of the tube was carried to the point where the discharge showed its different luminous portions clearly separated.

The manner of making the experiment was as follows: The electrodes were moved until the part of the discharge to be investigated came directly under the capillary opening *B*, a bit of test paper was then placed on the fluorite window and exposed to the action of the light for five minutes. The test paper was then removed and examined and a fresh bit put in its place. This operation was repeated four or five times, the conditions of pressure, current, and position being kept constant. The electrodes were next moved so as to bring another part of the discharge under the window and the operation was repeated. In this way the whole length of the discharge tube was explored. Experiments of this kind were carried out with pressures of 3, 2½, 2, and 1 mm; the current had always the same value, 0.01 ampere.

The results for hydrogen may be summed up by saying that the positions of the sources of the light of short wave-length coincide with the places of luminosity in the tube, and that the intensity of the most refrangible radiation may be judged by the intensity of the luminosity. Thus the starch paper shows some slight effect directly over the cathode, little effect in the Crookes dark space, a maximum effect at the head of the negative glow, no effect in the Faraday dark space, a feeble effect throughout the length of the positive column, and a fairly well-marked effect very near the anode. As long as the pressure has such a value that the luminosity of the negative glow is concentrated in a small volume the effect remains strong. When the pressure decreases and the negative glow begins to spread, the effect seems to decrease with decrease in the intensity of the luminosity.

A series of experiments similar in every way to those just described was next undertaken with air. The writer during his spectroscopic researches has been unable to obtain any evidence of radiation from nitrogen or oxygen in the region of light more refrangible than λ 1800. The light of short wave-lengths which is usually emitted by air in a vacuum tube is due to the presence of some impurity, probably carbon monoxide. It was to be expected, then, that if precautions were taken to exclude this impurity as far as practicable—for to exclude it entirely is almost impossible—the effects to be observed in air would be much less marked than those recorded in the case of hydrogen. This proved to be the fact, for with pure air in the tube no discoloration of the test paper could be detected at any point in the discharge with an exposure of five minutes.

In spectroscopic work the writer has been accustomed to use a discharge tube of the internal capillary type.[1] In this form of apparatus very little of the light which comes directly from the cathode is able to reach the slit of the observing instrument. It is of interest, therefore, to see if a tube of a different form might not yield better results. Some experiments were undertaken, accordingly, to compare the action of an arrangement like that shown in Fig. 2 with the behavior of a tube of internal capillary type. As far as can be judged from the starch paper test, the results are in favor of the older form of apparatus. For if *B* is used as a cathode and if the current is kept constant, a far feebler discoloration results in half a minute with the new tube than is produced in a like time with the older arrangement. It appears, therefore, that, for practical purposes, the concentration of the current and hence of the luminosity in the capillary more than offsets the greater effect which is found near the cathode.

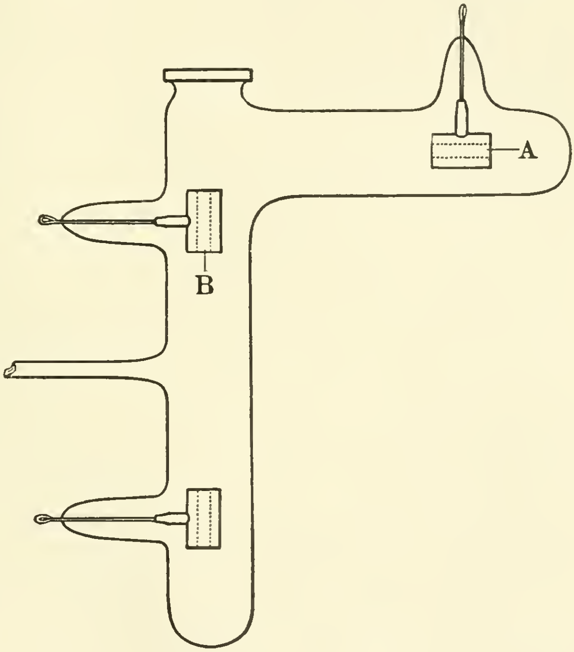

FIG. 2

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[1] *Astrophysical Journal*, 23, 192, 1906.

If the tube shown in Fig. 2 is filled with air it becomes obvious that though the phenomena under discussion are much less marked in this gas than in hydrogen, yet they still exist. For when A and B are used as electrodes and a current of 0.01 ampere is sent through the tube, a considerable discoloration of the test paper results in two minutes, and this effect is greater when B is cathode than when the connections are reversed.

The relation of the distribution of light of very short wave-length to the theory of electric conduction in a vacuum tube depends on the property of producing ionization which the more refrangible rays possess. Mr. Palmer has recently stated that light of shorter wave-length than λ 1800 produces considerable ionization and that this action increases with decrease in wave-length. The general effect can be demonstrated by a simple experiment. A discharge tube of the internal capillary type is filled with hydrogen to the pressure of 2 mm and closed by a fluorite window. A current of say 0.01 ampere is sent through the tube and the air from directly above the fluorite window is blown against a plate connected to a charged electroscope. The electroscope rapidly loses its charge. If now the fluorite window be protected with a piece of microscope cover glass about 0.2 mm thick and if the air be blown to the plate as before, the electroscope will retain its charge unaltered except for its normal rate of leak.

Professor Thomson[1] has shown by direct experiment that the radiation from a spark increases the conductivity of gases. He found that the effect was greatest at pressures of a few millimeters of mercury, and that it was most marked when the discharge took place in hydrogen. He also found that when the actions of different parts of the discharge were compared the effect followed the luminosity, with a maximum near the cathode.

Professor Thomson considers the ionizing radiation to be identical with the *Entladungsstrahlen* discovered by Wiedemann and, therefore, of a distinctly different nature from light of very short wave-length. The writer cannot altogether agree in this point of view, for it does not seem to him necessary to introduce a new form of radiation to account for the observed phenomena. The conditions under which Professor Thomson obtained the largest ionization effects are the very conditions under which light of very short wave-length is most readily produced.

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[1] *Proceedings of the Cambridge Philosophical Society*, 10, 74, 1899.

This subject very naturally raises the question as to the nature of the *Entladungsstrahlen* themselves. The writer has repeated the very striking experiments tried by Wiedemann and by Hoffman at atmospheric pressure, and his results and conclusions are identical with theirs. There is a "something" which comes from a spark discharge totally different in character from light of very short wave-length, which produces strong thermo-luminescence in certain mixtures of $CaSO_4$ and $MnSO_4$. To this something the name of *Entladungsstrahlen* has been given.

In case of the experiments tried at pressures much less than atmospheric the writer can no longer agree entirely with the opinions of the earlier investigators. Hoffman[1] states that at low pressures the spark in hydrogen sends out something which is able to penetrate fluorite and quartz and to produce thermo-luminescence. This is in strong contrast to the action of a spark in air, for then fluorite and quartz are very opaque to the new radiation. Hoffman explains the result by supposing that the fluorite sends out secondary *Entladungsstrahlen*. A far simpler explanation is, however, at hand, namely, that the agency which produces thermo-luminescence at low pressures is fundamentally different from that to which most of the effect is due at high pressures; for at low pressures the action of light of very short wave-lengths becomes important. Wiedemann and Hoffman very justly remark that their mixture of $CaSO_4$ and $MnSO_4$ is not sensitive to ordinary ultra-violet light; they were not aware, however, that their test compound is very sensitive to light of the shortest wave-lengths. The fact can be easily proved, however, by placing a specimen, prepared exactly as described by Hoffman, on the fluorite window of a discharge tube. With hydrogen in the tube and a current of about 0.01 ampere an exposure of one second is enough to produce strong thermo-luminescence in the specimen. If, however, the fluorite window is separated from the specimen by a cover glass about 0.2 mm thick, no result at all is produced even after a two-minute exposure.

It seems not unreasonable to suppose, therefore, that where the conditions are suitable for the production of light of the shortest wave-lengths some of the thermo-luminescent effects may be ascribed

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[1] *Wied. Ann.*, 60, 269, 1897.

to their action. The phenomena attributed by Wiedemann to *Entladungsstrahlen* alone are thus in all probability due to the result of two agencies: One, the *Entladungsstrahlen* proper, whose effect is most marked at atmospheric pressure; and the other, light of very short wave-length, whose effect is most pronounced in vacuum tube experiments. It is not impossible that both these agencies act to some degree at all pressures. At atmospheric pressure the *Entladungsstrahlen* are the important factor, though light effects do exist, as may be proved by focusing the light from an aluminum spark on the thermo-luminescent substance by a quartz lens. At low pressures light of short wave-length seems to be the more important factor, though the presence of some *Entladungsstrahlen* cannot be disproved.

Very recently de Broglie[1] has pointed out the existence of an ultra-microscopic dust which always accompanies the spark discharge. The erosion of the $CaSO_4$ surface under the spark suggests the idea that perhaps the mechanism of the *Entladungsstrahlen* depends on a sand-blast action in which this dust plays an important part.

In conclusion, to return to the phenomena of electric conduction through gases, it is extremely probable that the production of light from that part of the spectrum discovered by Schumann plays a distinct rôle in the mechanism of conduction. The importance of this rôle will obviously depend on the amount of light of short wave-lengths produced and upon its absorption by the gas itself. Thus the magnitude of the effect will vary greatly with the nature of the gas and will be larger for hydrogen than for most other gases. This agency adds a new factor to a system already sufficiently complicated. However, the idea of the ionizing influence of radiation has already been used by H. A. Wilson in constructing a theory of the mechanism of electric conduction in a vacuum tube.

Finally, it is of some interest to observe that the same general mechanism gives rise to visible radiation and to the vibrations of the highest known period, for wherever there is luminosity in a discharge tube there also light of very short wave-length is to be found.

JEFFERSON PHYSICAL LABORATORY
HARVARD UNIVERSITY
May 1, 1908

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[1] *Comptes Rendus*, **146**, 624, 1908.

OBSERVATIONS ON THE STRUCTURE OF THE ARC

BY W. B. HUFF

Several years ago the writer published in this *Journal*[1] a brief account of a spectroscopic study of the structure of the arc. A flat grating was used to give a series of images of the entire arc used as a source of light, no slit being employed. The results showed a marked difference between the parts of the arc. For small currents, the discharge at the negative pole took the form of a stream of light arising from a small area on this pole and spreading out into a cone as it approached the positive pole. The dispersed image of this stream showed that it was due to the metallic constituents of the commercial carbons used as terminals. The bands showed most strongly near the positive pole. Only for strong currents or for large amounts of metallic vapors in the arc did the region near the positive pole show the spectra of metals at all strongly. In a paper which appeared in a recent number of this *Journal*,[2] Humphreys notes the difference between anode and kathode spectra.

During the past year a research on the spark-discharge in a magnetic field has been carried on in this laboratory. Some observations made during the course of this work suggested a further study of the arc. The method was the same as the one previously employed and the photographs and visual observations in general confirm the earlier results, viz.: that for currents of only a few amperes, the arc between commercial carbons in air shows the spectra of the metallic constituents almost entirely in the region near the negative pole, where the discharge takes the form of a diverging stream; while the region near the positive pole, showing only a trace of these metallic spectra, gives the banded spectra very strongly. The bands may extend quite to the negative pole. A hissing arc or one that is unsteady usually shows the metallic spectra at both poles.

The form of the discharge, particularly of that part from the negative pole, is affected by the position of the arc. If the poles

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[1] *Astrophysical Journal*, 16, 27, 1902.

[2] *Ibid.*, 27, 194, 1908.

are vertical and the negative one is below, the longer parts of the negative discharge, forming the outer sheath of the arc, appear to reach the positive pole and to envelope it. The dispersed image of this part of the arc shows that sodium vapor forms the outside layer of the discharge, its image being much longer and wider than those due to the other metals. But in general the various images resemble one another in outline. They start at the negative pole as intensely bright and fairly sharp lines, but become broad and hazy toward the positive pole. The corresponding image near the positive pole is little more than a bright point, unless the current is large and much metallic vapor is present. A small piece of any metal introduced into the negative pole gives longer and stronger images in terms of the light from that metal. These images may of course extend nearly or quite to the corresponding ones from the positive terminal.

If the poles are vertical and the negative one is placed above, the discharge from this pole seems to descend and then to be curled outward and back upon itself by the upward rush of the heated air. This is especially well shown by the sodium, though all the images of the negative discharge are shorter than when the negative pole is below, and show flattening and widening at a short distance from their origin.

This convection effect from the heated air is very marked if the carbons are placed horizontal. If sufficient metallic vapor is present, the stream-like discharges proceed from both poles and are curled upward into a common vertical path. The horizontal parts of the streams from the negative pole are longer than those from the other terminal. This difference in length is probably due in part to convection from the unequally heated poles. It is possible, also, that the negative and positive discharges have different velocities.

If the poles are vertical and the positive one is below, the negative discharge disappears very quickly when the arc is broken. But if the negative pole is the lower one, the negative discharge appears to retreat slowly into this lower pole. A similar motion of the blue-green core may be observed at the positive terminal when it is the lower one. Whether there is actual motion, or merely a dying down of incandescence at a distance from the heated terminal, is difficult to determine. These general results of air convection have an obvious bearing on the question as to what length of arc can be obtained with a given current, as well as upon the resistance of an arc of given length.

If an aluminium plate is put between the poles, and the arc is made, that part of the double arc for which the aluminium is the positive terminal shows the banded spectrum of the oxide very strongly. This banded spectrum is hardly visible when the aluminium is the negative pole. With aluminium as the negative pole, the discharge is explosive and difficult to maintain, but with this metal as the positive terminal, the arc may be made much longer.

I have examined with the revolving mirror the arc from many combinations of metallic poles, but have not been successful in detecting any discharge which was strictly oscillatory.[1] It is frequently explosive, however, giving quite regular interruptions in the discharge, particularly when the negative pole is a metal.

The markings on a metal plate moved between the poles and serving one side as a positive terminal and the other as negative, are strikingly different. An effect analogous to Nobili's rings is easily obtained. The tracings on an aluminium plate which has served as a positive pole have their edges oxidized.

The trace on iron, examined under a microscope, is strongly corroborative of Trotter's[2] observation that parts of the arc may at times be in rapid rotation.

If a zinc rod is held to the positive pole and the arc is made, the rod gives a discharge which may shoot straight out from the rod in a direction apparently quite independent of the position of the negative pole. This rod used as the negative pole gives a violently explosive discharge. The other metals tried gave similar results. The positive and negative discharges from a given metal are quite different in appearance. Each is deflected by a weak magnetic field, the direction being that which would be shown by a stream of charged particles.

The musical arc[3] was also used in this study of the discharge.

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[1] Upson, *Philosophical Magazine*, (6), 14, 126, 1907.

[2] *Proceedings of the Royal Society*, 56, 262, 1894.

[3] Austin, *Bulletin of Bureau of Standards*, 3, 325, No. 2, 1907.

As is well known, this form of discharge is produced by connecting in parallel with the arc a system having considerable self-induction and capacity. Oscillations are set up which have approximately a period $2\pi\sqrt{LC}$ and these, acting upon the arc, produce a musical note. Clear tones of nearly constant pitch may be obtained by using vertical poles, the positive one being below. A small carbon is better for the positive terminal, since it soon becomes pointed and thus the arc cannot by wandering change its length and therefore change the pitch of the note emitted.

The result of studying such an arc with a revolving mirror shows that for the arc between carbons in air, the presence of the blue-green core at the positive pole is a necessary condition for a sustained note. I have not been able to produce this musical discharge for more than a moment between metallic poles; nor at all between carbon poles at atmospheric pressure when much metallic vapor was present. But the moment the core of the arc appears at the positive terminal, the oscillations may begin.

The revolving mirror shows that the oscillations of this core are very marked. The negative discharges from metals mixed with the carbons do not show any oscillations until the core begins to move. When the oscillations are once set up, however, the spectrum of the entire arc obtained from a grating revolving rapidly, shows interruptions in the bands from the region near the positive pole and also in the discharges from the negative pole. These interruptions seem to extend throughout the spectrum and, as would be expected, have the same period.

The discharge as a whole does not appear oscillatory, since the core does not appear first at one pole and then at the other. It seems to move out from the positive pole and then back toward that pole. Nor have I been able to detect the metallic discharge except at what would be the negative pole of the arc for steady current.

This form of arc may therefore be considered as an interrupted discharge rather than one which is strictly oscillatory; as if it were the result of superposing an oscillatory discharge upon the steady arc discharge, the impressed effect not being sufficiently intense to cause the poles, although intensely heated, to emit particles to such an extent as to render the results of the impressed oscillations easily noticeable in the spectroscopic examination of the arc as a whole.

A second carbon joined in parallel with the positive one forms an arc with the negative terminal when it is brought into the outer sheath or flame of the arc. But if this auxiliary terminal is joined in parallel with the negative pole, it arcs with the positive only when it has pierced the outer flame and reached the core. Therefore for the existence of a carbon arc in air it is necessary that at least a part of the negative stream should reach the core which is at the positive terminal.

It is well known that a comparatively weak magnetic field breaks the arc, the discharge as a whole being deflected as a wire would be if it carried the current.

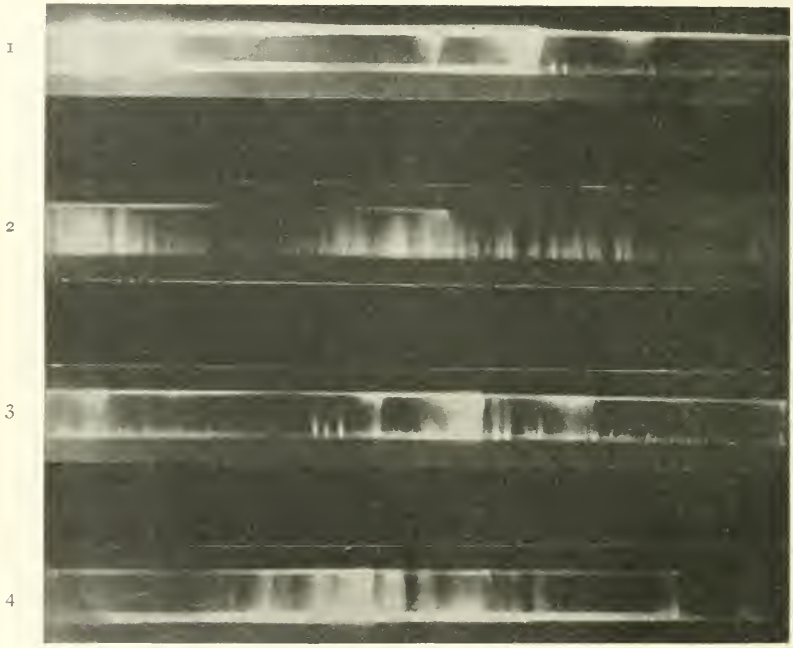
A bar magnet was set swinging near the arc and rough measurements were taken of the resulting deflections of the various images formed by the grating.

If the arc-terminals are of small diameter and the current only a few amperes, these images are fairly well defined. Every part of the arc appeared to be deflected, and to about the same extent. The fact that the various images of the negative discharges differed from one another in length as well as in outline at the broad extremity of the visible discharge rendered accurate measurements difficult.

More careful observations were made on the arc in the nearly uniform field obtained from two coils carrying a current. The discharges from small amounts of zinc and sodium deposited over the surface of the negative pole were of about the same length, although the sodium image appeared to have its origin in the outer layer of the discharge, as if the sodium vapor surrounded that of the zinc. With iron as the negative pole, the images were narrower and sharper.

The results of observations on the separate images produced by the grating indicate that the magnetic field deflects all parts of the negative discharge to the same extent. The series of spectral images of the negative discharge from all of the elements which were introduced into the arc at the negative pole showed deflections in the magnetic field.

Using a short arc, it is easy to obtain upon the negative pole a deposite of carbon from the positive terminal. This deposit takes the "mushroom" form noticed by many observers. It is evident, therefore, that a stream of particles may be given off by the positive pole. That these particles are charged seems to be shown by the effect of a magnetic field upon the discharge giving the deposit.



Plates Taken with Entire Arc as Source

1.—Carbon poles, the upper positive. Current 6 amperes.
2.—Upper pole carbon, positive; lower pole carbon. Current 10 amperes.
3.—Poles carbon on which copper has been deposited; the upper one is positive. Current 6 amperes.
4.—Same as No. 3, except that negative pole is above.

The general results of these observations may be stated as follows:

For weak currents, the discharges at the two poles of a given arc are essentially different in character.

For heavy currents and large amounts of metallic vapor in the arc, the structure of the discharge is less well defined.

The discharge from the negative pole arises from a small, intensely heated region and spreads out toward the positive terminal. Its appearance and its behavior in a magnetic field suggest that it is a stream of charged particles arising from an incandescent solid.

An examination of the images obtained by using the grating upon the entire arc as a source shows that all images of the luminous discharge are deflected by a magnetic field.

From these results it may be inferred that the arc is maintained by the convection of charges which are associated with particles having their origin at the poles. The nature and size of these particles, as well as their velocity, would of course depend in part upon the gas in which the discharge takes place, and upon the pressure. Their velocity is extremely low compared with that of the particles associated with the discharge in a vacuum tube. Indeed it is probably lower than the velocity of the slowest particles which emit or cause the emission of light in the spark-discharge at ordinary pressures.

The negative arc-discharge seems to be similar to that which is known to be emitted by incandescent bodies. It may fairly be considered analogous to the kathode discharge in a vacuum tube. In appearance this negative part of the arc-discharge is quite similar to that from the negative terminal of a non-oscillatory spark. It is also strongly suggestive of those parts of the oscillatory spark which are negatively charged, easily deflected by a magnetic field, and which give spectra characteristic of the spark terminals.

Further experiments with the arc in a magnetic field are in progress. Quantitative results would have a direct bearing upon the question as to whether, in the various parts of the arc, the particles carry charges which are simple multiples of a common unit.

Physical Laboratory
Bryn Mawr College
April 1908

THE RELATIVE INTENSITIES OF SPECTRUM LINES

By P. G. NUTTING

Recent advances in spectroscopy have added greatly to our store of data bearing on variations in the relative intensity of spectrum lines produced by varying current, capacity, inductance, temperature, pressure, and other like conditions of excitation. That this accumulation of facts is capable of reduction to but a very few variables is believed by most spectroscopists, but no one appears to have attempted the task. In this paper I shall attempt to show that a single variable, or at most two, is sufficient.

Every spectrum line of every element appears to require a certain well-defined minimum of some energizing influence for its production. This is quite different from the thermal emission of solids, which is supposed to continue down to the absolute zero of temperature. If this minimum of exciting influence is exceeded, the spectrum line increases continually in intensity with increasing excitation. If this minimum is expressible without hypothesis, in terms of a known measurable quantity, we have an ideal basis of classification of lines.

For the sake of brevity, let us speak of "hard" and "soft" lines, the "harder" the line the greater the initial excitation necessary and the greedier of energy when the supply is generous. In most spectra lines may be grouped according to hardness, frequently into but two general groups, the primary and secondary spectra, differing widely in conditions of excitation but always overlapping to some extent; that is, the soft or primary spectrum does not disappear as soon as the hard or secondary spectrum appears. This overlapping is least with the acid-forming elements.

Graphically, if we plot energy of line against total energy, the curves (which are very nearly straight lines) for soft lines will intercept the axis of total energy near the origin, while the harder lines are characterized by a larger intercept and in general by a larger angle of interception as well. In the case of a radiating black or gray body all such curves pass through the origin tangent to the total energy axis.

Several years ago the writer[1] gave the steepness of the wave-front through a gas as condition for the preponderance of the secondary over the primary spectrum. Crew[2] almost at the same time concluded that "a high E. M. F., rapidly changing, is a probable *conditio sine qua non* for the appearance of spark lines in arc spectra." Both might better have expressed their results in terms of potential gradient.

Let us consider arc, spark, and vacuum-tube spectra from the single standpoint of potential-gradient in the luminous gas. The lowest gradients are obtained in heavy current arcs and Plücker tubes with wide capillary; in the former case the low gradient is due to the heavy current, in the latter to low gas-pressure. Higher potential gradients are obtained in arcs with very small current, Plücker tubes with fine capillaries and sparks with small capacity and large inductance. The highest potential-gradients are found in sparks and other interrupted arcs, the gradient increasing with the amount of capacity in circuit and with the impressed voltage. Gradients vary from about 20 to 80 volts per cm in ordinary arcs and tubes up to thousands of volts per cm in condensed sparks.

Consider the simple case of hydrogen in a Plücker tube. To obtain the white glow, giving the primary spectrum, we use a capillary of several mm diameter, gas at the pressure of its maximum conductivity, and a moderate steady current—just the conditions for low potential-gradient. To get the red secondary it is sufficient merely to use a very fine capillary, thereby raising the potential-gradient from about ten up to several hundred volts per cm. Increasing the density of the hydrogen helps because it increases the gradient. The short cut from primary to secondary lines is of course to use a series spark with capacity, provided the gas density is sufficient (1 cm or over) to support a high gradient. Inductance reduces the gradient down to a minimum, beyond which it is inoperative.

In the arc, potential-gradients may be similarly varied but under more complex conditions. Varying the length of an arc does not greatly affect either the potential gradient within it nor its spectrum, nor does varying the pressure of the surrounding atmosphere over a wide range from one-tenth to ten atmospheres. As to the relation of

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[1] *Astrophysical Journal*, **20**, 135, 1904.

[2] *Ibid.*, **20**, 284, 1904.

potential-gradient to current, external resistance, and impressed voltage, we must consult a Kaufmann diagram. This shows that potential-gradient is practically a function of current alone, but in a manner entirely different from that indicated by Ohm's law. For currents of from one or two amperes up, it is low and nearly independent of the current, but below one ampere it increases very rapidly with decrease of current, reaching thousands of volts at a few hundredths of an ampere. A mercury arc or Nernst filament will operate very well on a 5000-volt circuit at but slightly decreased efficiency but with a very slight current and enormously increased gradient.

A discussion of the Kaufmann diagram as applied to arc, spark, and vacuum tube has been given by the author[1] together with the results of work on the spectra of arcs at 4000 volts and 0.05 ampere. The appearance of "hard" or spark lines in low current arc spectra had previously been noted by many observers, but they are especially striking in the writer's spectrograms taken under the extreme conditions mentioned. In some cases, these lines appear only within about $\frac{1}{2}$ mm of the electrodes of the 2 mm arc, as though not much of the electrode metal was vaporized, while with antimony, bismuth, and cadmium, the spark lines extend quite across the arc.

In the condensed spark without inductance, the front of the pilot discharge must have a potential-gradient not much below the dielectric strength of the intervening gas. The remainder of the discharge is probably at a very low gradient, approaching that of a direct-current arc. Hence such a spark gives both spark and arc lines. Inductance and resistance lower maximum gradients by smoothing out the current wave. The spectrum of a spark rendered dead beat by series resistance can scarcely be distinguished from that of a low direct-current arc.

TEMPERATURE AND PRESSURE

We have considered the intensity of a spectrum line as expressible in terms of but two constants and one independent variable. These two constants are the intersection and slope of the curve relating line energy to total energy. The independent variable is the specific

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[1] *Bulletin of Bureau of Standards*, 1, 399–416, 1905.

energy content of the luminous gas, but, since that quantity is difficult of determination, we have spoken instead of potential-gradient, its chief component in cases of electrical excitation and a quantity very nearly proportional to it. Let us consider briefly the effects of temperature and pressure as parameters.

We have every reason to suppose that an electric current sufficient to bring a gas to the neighborhood of its maximum conductivity brings all the particles of the gas into action. The "saturation" of the current indicates complete ionization on the one hand, and on the other the ratio of line width to line intensity[1] indicates that an increase in the current does not bring into play more particles of the same kind but only excites more intensely those already radiating. The completeness of the excitation is remarkably independent of the kinetic motions of the gas particles, be they fast or slow.

But on merely heating a gas to a high temperature, only a few of the faster-moving particles are at first raised above the critical condition of radiation. If, however, a gas could be maintained at so high a temperature that, say 95 per cent. of the particles were above their critical condition, then thermal excitation would produce radiation comparable with electrical excitation. J. J. Thomson's simile of burning the kitchen to boil the pot seems hardly fair, at least it is not the inefficiency of the gas as a radiator, but the difficulty of getting energy to it rapidly enough, that makes thermal excitation inferior to electrical.

But temperature and pressure together may produce large local supplies of energy within a gas by thermo-chemical processes under such conditions as are supposed to exist in the sun and hotter stars. Consider a large mass of a mixture of two gases which combine freely at one temperature and pressure and which dissociate at some other temperature and pressure. Then a long-continued slow change with absorption of heat, followed by a slight gravitational displacement, might cause an enormous local liberation of energy continuing over a longer period of time as the mass departed from homogeneity.

If stellar luminosity is due chiefly to such causes, then luminosity should depend upon the mass as well as upon the temperature of the star, for it would be greatest with enormous pressure- and density-

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[1] *Astrophysical Journal*, **24**, 116, 1906.

gradients. The point to be emphasized here is that for thermochemical as well as other forms of excitation, spectroscopic evidence is in favor of relating the intensity of each spectrum line to a single variable and two constants.

In conclusion, I wish to enter a plea for a simpler and broader basis for spectroscopy and a basis as free as possible from either assumption or speculation. Some such general variable as that here suggested is required to sweep away the mystery surrounding arc, spark, and tube spectra, and rescue spectroscopy from a seemingly hopeless fortuity.

Bureau of Standards
Washington, D. C.
May 1908

NOTE ON SERIES IN ALKALI METAL SPECTRA

By F. A. SAUNDERS

In a dissertation of unusual interest, A. Bergmann has recently announced, among other new series, one in the spectrum of caesium, which Runge[1] thinks is related to the first subordinate series of that element. Ritz[2] has very lately noted the fact that this series is not entirely new and that there are very serious objections to Runge's proposition. I should be glad to be allowed to add a few comments.

At the time when my work on these spectra was published[3] I endeavored to bring every line in the arc spectrum of caesium into the series classification. There was an odd one at λ 9171 for which I imagined an (undiscovered) mate, thus making up a pair. There were six other pairs in an obvious series arrangement, which I was obliged to split into two series to accommodate this questionable pair. On coming back to the matter again, I saw (it should have been apparent before) that λ 9171 is needed elsewhere, and that the six pairs, with another, discovered by Bergmann, rightly belong, as he has classified them, in one series, whose approximate equation he has given. Since he was not acquainted with my measurements, I think it worth while to tabulate, below, the complete series, as far as now known, and recalculate the formula, using the best values for the wave-lengths.

I have already pointed out that the pairs of all first subordinate series are really triple. As examples I might mention the groups *Cs:* λ 6983.8, 6973.1, 6723.7; *Rb:* λ 7759.5, 7757.9, 7619.2; *Ca:* λ 3181.40, 3179.45, 3158.98. The first of these lines is always relatively faint, but is the more important theoretically, since the constancy of wave-number difference holds between it and the short wave-length line of the three, and not between the two strong lines, as was first supposed. Now, the line λ 9171 of caesium belongs to just such a "pair" (9211, 9171, 8766) of the first subordinate

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[1] *Astrophysical Journal*, 27, 158, 1908, and *Physikalische Zeitschrift*, 9, 1, 1908.

[2] *Physikalische Zeitschrift*, 9, 244, 1908.

[3] *Astrophysical Journal*, 20, 188, 1904.

series, and thus all the lines of the arc spectrum fall into the series classification.

The columns of the table show (1) the observed wave-length, (2) the stated error, (3) the value of the integer m in the series formula, (4) the initial of the observer (B = Bergmann, L = Lehmann, S = the writer), (5) the wave-length calculated from the formula given below, (6) the difference between the observed and calculated wave-lengths, and (7) the wave-number differences for the pairs. Calculated values are given for the possible first term of the series for which $m=2$. This has not yet been certainly observed, and Ritz points out that it may not exist after all. The formula is calculated using wave-lengths reduced to vacuum, and runs as follows:

$$\frac{1}{\lambda}=\left\{\begin{matrix}16899.6\\16802.0\end{matrix}\right\}-\frac{109675}{(m+0.9762)^2}.$$

THIRD SUBORDINATE SERIES OF CAESIUM

Wave-Length	Error	m	Observer	Calculated Wave-Length	Calc.—Obs.	Wave-Number Difference
		2		22620.		97.6
		2		22437.		
10127.	?	3	B	10134.	+7.	97.4
10028.	?	3	B	10034.	+6.	
8082.0	0.5	4	L	8080.0	−2.0	96.2
8019.6	0.5	4	L	8016.7	−2.9	
7280.5	1.	5	S	7280.5	0	98.5
7228.8	1.	5	S	7229.0	+0.2	
6872.6	1.	6	S	6871.7	−0.9	97.4
6826.9	1.	6	S	6825.9	−1.0	
6630.5	1.	7	S	6630.3	−0.2	97.3
6588.0	1.	7	S	6587.7	−0.3	
6475.	2.	8	S	6475.	0	99.
6434.	2.	8	S	6434.	0	
6359.	5.	9	S	6368.	+9.	84.
6325.	5.	9	S	6329.	+4.	

It is to be noticed that the formula is very simple, since it contains only two adjustable constants (109675 is the universal constant used by Ritz) and yet the observations are sufficiently well represented. It is likely that another constant would have to be added to make the formula include the pair near 2 μ, if that were known.

It may be thought that the line λ 6588 comes too near the relatively strong *Cs* line 6587.3 of the second subordinate series to be really measurable. The line 6588 is 40 Å. broad on some of my negatives, and lies like a cloud "behind" the sharp series line. Comparison with the other series lines, such as 6355.3, which have no such halo, shows that my interpretation is necessary, but the measurement is, of course, very uncertain.

Runge believes that this series may be found to be a second sort of principal series, closely related to the first subordinate series. Ritz has already objected on the ground that the wave-number differences are constant. I should like to add that the stronger line of each pair has the greater wave-length; this is characteristic of all subordinate series and is just opposite to the principal series arrangement.

The third subordinate series, found by Lenard in the sodium spectrum, seems to be very similar to this one in the caesium spectrum. It presents a similar hazy aspect, is equally faint, and has a wave-number difference which does not agree with that of the usual series; but it seems to run to the same end as these, wherein it differs from the new caesium series. Bergmann finds a new line at λ 12680 in the sodium spectrum. This is probably an unresolved pair belonging to Lenard's series. If we consider it so, it can be included with the others by a formula similar to that of Ritz, with one small modification. The table shows how well this can be done; it is to be noted that the lines are not very accurately measured.

THIRD SUBORDINATE SERIES OF SODIUM

Observed Wave-Length	Error	Calculated Wave-Length	Calc.—Obs.	Wave-Number Differences
12680.	?	12680.	0	Not resolved
7377.4	0.4	7377.5	+0.1	14.72
7369.4	0.4	7369.4	0	
5532.7	0.4	5533.0	+0.3	14.77
5528.2	0.4	5528.5	+0.3	
4918.4	1.	4917.3	−1.1	18.
4914.0	1.	4915.5	+1.5	
4629.5	1.	4630.2	+0.7	18.
4625.5	1.	4626.3	+0.8	
4472.5	2.	4470.8	−1.7	Not resolved
4372.	5.	4372.5	+0.5	Not resolved

The formula runs:

$$\frac{1}{\lambda} = \left\{ \begin{matrix} 24549.8 \\ 24535.0 \end{matrix} \right\} - \frac{109675}{\left\{ m - 0.5772 + \dfrac{0.6778}{1 - \dfrac{6.517}{m^4}} \right\}^2}$$

It contains four adjustable constants, and is not to be recommended for its simplicity. I have already expressed my conviction that almost any sort of a four-constant formula can be used to represent a series which is inaccurately measured. Unfortunately all four constants seem to be required in many cases, especially when the series is completely known. A universally applicable three-constant formula is still to be found, notwithstanding the brilliant work of Ritz, and others. This particular sodium series is not a good one to use to help decide on the best type of formula, as it is so hazy and faint, but there are several others that are available. Long and intimate acquaintance with some of these, especially Rydberg's series of single lines in magnesium, has brought me to the opinion that none of the existing formulae will quite perfectly represent them. Hence I am at present driven to make use of such a one as above.

Syracuse University
May 1908

POLARIZED FLUORESCENCE OF METALLIC VAPORS AND THE SOLAR CORONA

By R. W. WOOD

The presence of radially polarized light in the solar corona has always been regarded as almost proof positive that a part at least of the light is sunlight, scattered by very small particles. If this is the case we should expect to find the Fraunhofer lines in the spectrum Now the majority of the observations which have been made of the spectrum of the corona show that these lines are absent, though in a few cases very slight evidences of them have been seen. A very slight trace of them could undoubtedly be explained by superposed skylight. To account for the absence of these lines it has seemed necessary to explain the emission of the corona as due, in part, to incandescent liquid or solid particles. This view is, however, difficult to reconcile with Abbot's bolometric observation of a cold corona. As I pointed out in an article on the nature of the corona published in this *Journal* in January 1901 (**13**, 68), the absence of the longer waves could be explained by the smallness of the scattering particles, for it was found that the minute carbon particles in a candle flame scattered blue and violet light powerfully, green to a much less degree, and red not at all. There remains, however, the matter of the continuous spectrum, for light emitted in virtue of incandescence should show marked heating effects. Upon the whole it appears to me that no theory of the corona, advanced up to the present time, explains the phenomenon in a satisfactory manner.

I have recently found, however, that the fluorescent light emitted by comparatively cool metallic vapors, when a powerful beam of light is passed though them, is very strongly polarized, and that moreover the percentage of polarized light is almost exactly what we should expect in the corona, if that phenomenon were due to the fluorescence of a great cloud of mixed metallic vapors surrounding the sun, under the influence of the very intense illumination to which it is subjected.

Thus far I have detected the presence of polarized light in the fluorescence of sodium, potassium, and iodine vapor.

A Savart polariscope was used, and the percentage of polarization measured by compensating it with one or more glass plates, which could be rotated on a vertical axis, furnished with a graduated circle.

The apparatus used in the experiments is shown in Fig. 1, a description of which was published in this *Journal* in September 1903 (**18**, 96). If the incident light was plane polarized to start with (the vibrations or electric vector being in a vertical plane), 30 per cent. of the fluorescent light was found to be plane polarized. If the exciting beam was unpolarized the percentage dropped to fifteen.

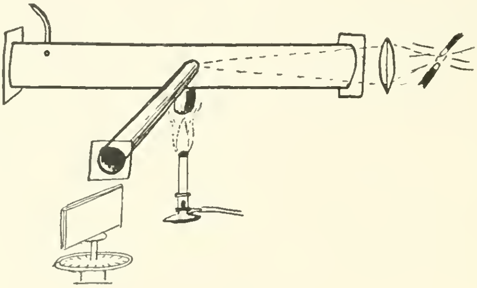

Fig. 1

The fluorescent cone of light was observed through the lateral tube at an angle of 90° with the exciting beam. The results in detail, together with the precautions taken to eliminate all possible sources of error, such as the presence of fog in the tube, will be found in the current number of the *Philosophical Magazine*. The fact that the percentage of polarized light, when the exciting light was unpolarized, is almost exactly equal to that shown by the corona, is most suggestive. The corona, it is true, shows only about 11 per cent., but it must be remembered that the angular convergence of the rays from the sun at a distance of one solar diameter is much greater than that obtained from the double convex lens which furnished the exciting beam in the laboratory experiment. This would make the percentage of polarization slightly less in the case of the corona (coronal polarization, 11 per cent.; laboratory experiment, 15 per cent.).

The fluorescence spectrum of a mixture of metallic vapors would undoubtedly appear continuous, or practically so, with all dispersions that have ever been brought to bear upon the corona. The fluorescence spectrum of sodium vapor alone is made up of thousands of very fine lines arranged in groups or bands. The bands can be seen with instruments of low dispersive power. The color of the fluorescent light is a very pure and brilliant green. (See paper in the *Philosophical Magazine* for May, "The Resonance Spectra of Sodium Vapor.") A mixture of potassium and sodium vapors gives a brilliant white fluorescence tinged with yellow.

It is clear that with a suitable mixture of vapors we could have a fluorescence tinged with almost any color we pleased according to the proportion of the vapors constituting the mixture. The majority of observers seem to be of the opinion that the solar corona emits a light which is far from being white. The color may be in part due to the so-called green coronium line, but fluorescence would explain it at once, as well as the absence of radiant heat, for it is doubtful if the fluorescence spectrum extends very far beyond the visible red. An observation of Sir Norman Lockyer is of interest in connection with a fluorescence theory of the corona.

In his *Chemistry of the Sun*, p. 365, he writes as follows regarding his observation of the spectrum of the corona at the eclipse of 1882: "The spectrum of the corona, as I saw it in Egypt, was of the most complex nature. It was distinctly not a continuous spectrum such as[1] that given by the lime light. Instead of the gradual smooth toning seen, say, in the spectrum of the lime light, there were maxima and minima, producing an appearance of ribbed structure, the lines of hydrogen and 1474 being of course over all. Of other bright lines distinct at any great distance from the photosphere I saw none, nor any very marked absorption lines, not even D or *b*. *But what I really did see was as if all the banded spectra I had ever seen were superposed.* My instrument was a short focus photographic objective of six inches aperture and one flint prism, so that the light in the spectrum was ample. One could be certain of what one saw."

Inasmuch as band spectra appear to be characteristic of fluorescing metallic vapors, this observation is certainly very suggestive. A

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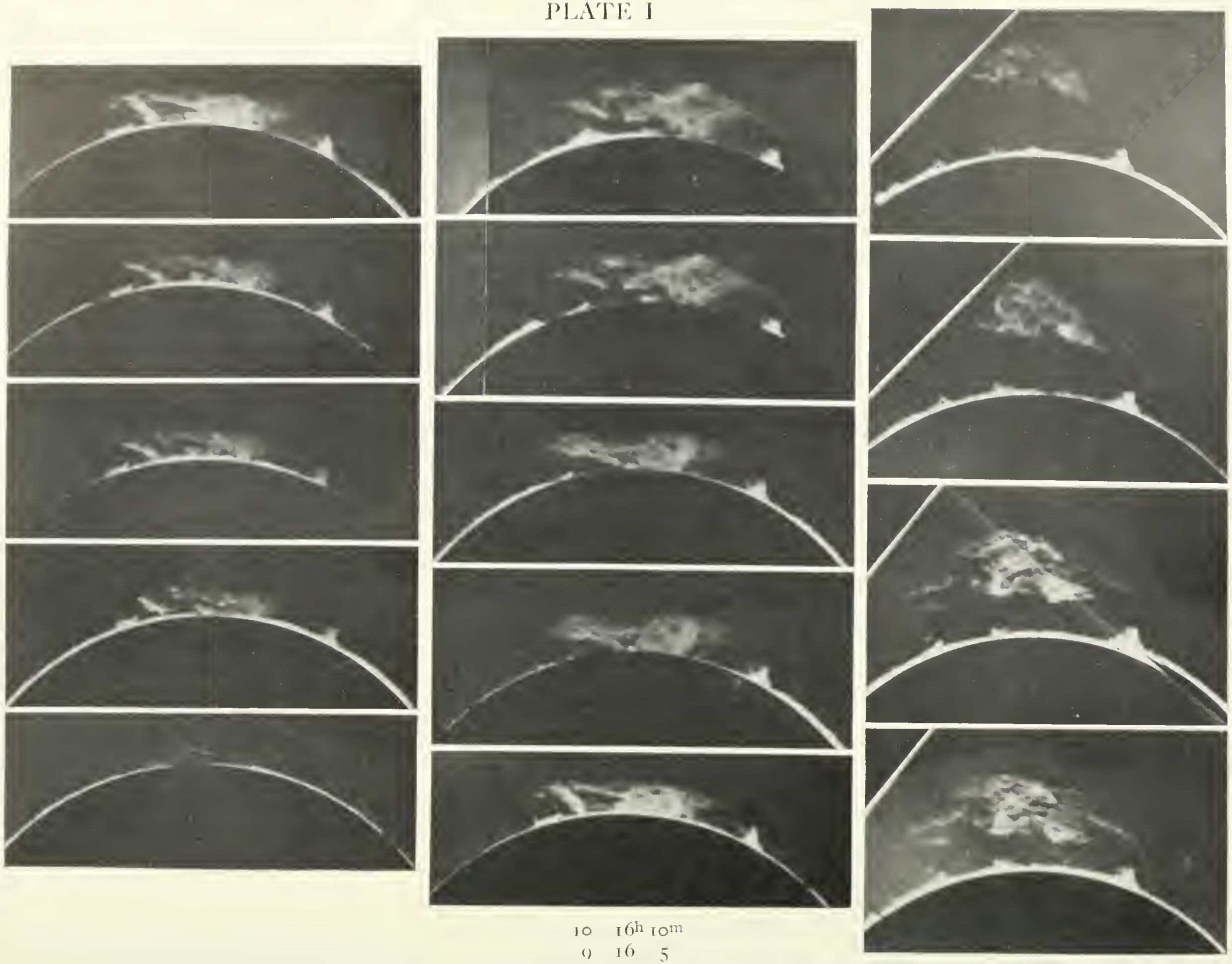
[1] Lockyer used the word "resembling," which makes his meaning a little ambiguous.

spectroscope of low dispersion will often give unmistakable evidence of faint bands, when an instrument of higher power fails to reveal any trace of them. This I have frequently noticed in studying the spectra of fluorescent vapors.

It appears to me to be quite possible that the green coronium line, as well as the other bright lines, which have been observed in the corona's spectrum and which have not been identified with any known terrestrial substance, may be the fluorescent lines of some well-known substance or substances. As I have shown, the fluorescent lines of sodium vapor do not coincide with any emission lines obtained in any other way. It is even possible that the Fraunhofer lines may have their origin in coronal absorption. This, however, is a question which can be better discussed by those who are engaged with the study of solar physics. It seems certain, however, that we are no longer forced to attribute coronal polarization to the scattering of light by small particles. The fluorescence of a metallic vapor is quite a different phenomenon, as there is a change of wave-length.

Johns Hopkins University
May 15, 1908

PLATE I



5
$11^h 5^m$

4
$10^h 1^m$

3
$9^h 54^m$

2
$9^h 38^m$

1
$8^h 23^m$

10 $16^h 10^m$
9 16 5
8 14 36
7 14 30
6 11 13

14
$17^h 41^m$

13
$17^h 32^m$

12
$17^h 17^m$

11
$17^h 11^m$

PROMINENCE OF FEBRUARY 18, 1908 (Indian Standard Time)

A LARGE PROMINENCE

BY J. EVERSHED

By a fortunate chance the writer was able to secure a good series of plates, showing the development and final rapid ascent of a very large prominence. This was of a type that has seldom been recorded previously.

At this observatory it is part of the usual routine with the spectroheliograph to secure daily two good plates of the prominences. These are obtained ordinarily between the hours of eight and nine in the morning, when definition is at its best. On February 18, 1908, the second plate exposed turned out to be rather a poor one, but the first, exposed at $8^h\ 23^m$, was good. The prominences were, however, small, and there seemed to be nothing of special interest on the limb. Fortunately, it was thought worth while to expose a third plate. This was done at $9^h\ 38^m$, and the result showed that there had occurred a remarkable development of a prominence shown faintly in the first two plates, extending from the position-angle 89° to 127°.

Realizing the unusual nature of the newly developed group of prominences, arrangements were made to continue photographing this part of the limb throughout the day, which was fortunately perfectly clear from sunrise to sunset. It should be stated that visual observations in the $H\alpha$ line, were made between $8^h\ 40^m$ and $10^h\ 30^m$, and this region of the limb was sketched by Mr. Sitarama Aiyar between $8^h\ 43^m$ and $9^h\ 3^m$. His drawings show a moderately bright mass of prominences, extending from position-angle 89° to 121°, having bright condensations at 91° and 97°. The sodium and magnesium lines were noted as bright at 91°. The main mass was estimated at $50''$ in height at $8^h\ 50^m$, and $85''$ an hour later. A smaller but bright prominence was situated at P. A. 135°, and this also increased during the observation from $45''$ to $80''$.

Twenty photographs in all were secured during the day, two exposures being made on each plate after the first three, and fourteen of these are shown in the accompanying reproductions (Plate I). The definition became very poor between 12^h and 17^h and good guiding was then impossible, the image moving bodily on the slit plate. This is shown in the irregularities of the limb seen in Nos. 7 to 10. Later, the definition improved, but the last plate, exposed at 18^h 2^m, was much underexposed, owing to thick smoke from forest fires passing over the sun's disc. The image No. 12 is somewhat distorted through the electric guiding control failing to act; and the disk excluding the photosphere had to be moved, to prevent fogging the plate. The position-angle of the small bright prominence seen in all the photographs except No. 1 was 135°, equal to solar latitude −63°, and from this position the prominence extends to P. A. 89°, equal to solar latitude −17°.

Notwithstanding the very sudden appearance of such an enormously extended mass between the hours of 8 and 9, the subsequent increase in size took place quite slowly. Visual observations in the *Hα* line showed scarcely any evidence of motion in the line of sight, such as usually accompanies great eruptions. The actual increase in height determined from measurements at a definite point on the limb (P. A. 116″) is shown in the following table, which also gives the approximate rate of ascent in the mean interval between successive pairs of photographs. The most striking feature is the accelerating velocity with which the entire mass leaves the sun. A reference to the last four photographs of the series here given will show this clearly. The prominence also appears to diminish in brightness as it ascends, but this is no doubt due in part to the rapidly diminishing altitude of the sun, which at 17^h 41^m was only 8°, and at 18^h 2^m was less than 3° above the horizon; the two images in the last plate were too faint for reproduction.

Another feature of interest is the long filament joined to the main mass and arching over the small bright prominence. In the negatives it appears to be connected with the top of the small prominence at 11^h 5^m but becomes disconnected at 14^h 36^m; at 17^h 11^m it is joined to the chromosphere beyond, at P. A. 139°. The movement of the whole mass, from this time on, is greatest at the parts most remote from the filament, and gives one the impression that the latter acted like a flexible cord, holding one end of the mass to the sun and forcing it to swing out in a curve.

HEIGHTS OF PROMINENCE MEASURED AT POSITION-ANGLE 116°

Number of Plate	Indian Standard Time*	Mean Height in Seconds of Arc	Approximate Velocity of Ascent
	h. m.		km per sec.
271	8 23	...	
274	9 38	81	
			12
275	9 54	100	
	10 1		
			1.2
276	11 5	107	
	11 13		
			2.5
279	14 30	150	
	14 36		6.7
280	16 5	202	
	16 10		
			24
281	17 11	337	
	17 17		
			37
282	17 32	405	
	17 41		
			84
283	17 56	Too faint to measure	
	18 2	585	

* $5^h\ 30^m$ in advance of Greenwich mean time.

The writer has met with only two previous examples of prominences having the same characteristics as the one of February 18 last, and in neither instance was it possible to follow out the changes at all completely. The first was observed in its earlier stages at the writer's private observatory at Kenley, on the date October 3, 1892. Between 7^h and 9^h G.M.T. it was a large mass of complex filaments, extending from latitude $-21°$ to $-39°$ on the S.E. limb, with small bright prominences at $-15°$ and $-42°$. At 2:00 P.M. Kalocsa M. T., it was observed by Herr Fényi, and at this time had attained the height of $8' 51''$. His measurements indicated a rapid rise of the upper part, which showed a mean velocity exceeding 36 km per second. At $2^h\ 55^m$ nothing remained of the higher part. Displacements of the spectral lines did not occur.[1]

The other prominence, apparently of the same type, was photographed here, on April 9, 1907. Like the former, it consisted of a

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[1] *Astronomy and Astrophysics*, 12, 38, 1893.

huge mass of interlaced filaments. It extended from solar latitude +16° to +38° on the east limb. Only three photographs were obtained, and the heights measured on these are as follows:

No. of Plate	I. S. T.	Height	Approximate Velocity of Ascent
452...........	$8^h\ 34^m$	105″	7 km per sec.
456...........	8 55	117	12 km per sec.
457...........	9 13	135	

An increasing rate of ascent is here indicated. The prominence had disappeared on the following day. It would be interesting to know whether this prominence was observed in its later stages elsewhere.

It is perhaps worthy of remark that the disc photographs in K light, obtained on the dates April 9, 1907, and February 18, 1908, show no flocculi nor any kind of disturbance at or near the positions of the prominences.

Solar Observatory
Kodaikanal, South India

MINOR CONTRIBUTIONS AND NOTES

REMARKS ON THE USE OF THE SELENIUM CELL IN PHOTOMETRY

Within the past few months Messrs. Stebbins and Brown, of the University of Illinois, have presented several papers[1] on the application of the selenium cell to photometric measurements. Inasmuch as these papers contain statements which are liable to be misleading, I have thought it desirable to make a few remarks upon the subject in general.

In his most recent paper on "The Color-Sensibility of Selenium Cells," Mr. Stebbins gives a number of curves representing the variations of resistance of selenium with the wave-length of the incident light. As a matter of fact, these curves are not true sensibility curves as no account has been taken of the distribution of energy in the spectrum of the source of light (in this case, the sun). Several years ago I had occasion to determine the sensibility curves of a number of selenium cells.[2] As was pointed out at that time, the energy carried by each bundle of approximately homogeneous radiations, before being permitted to fall upon the cell, was made the same in all cases (the energy measurements being carried out by means of a Rubens' thermopile and galvanometer). Such curves, as contrasted with those of Mr. Stebbins, will not vary with the character of the source but will represent only the peculiarities of the cell itself. If the distribution of energy in the spectrum used by Stebbins were known, it might be possible to apply the desired corrections, but, unfortunately, this is impossible at the present time. Although the solar energy curve is known (having been determined by the use of prisms), the fact that Stebbins and Brown employed a grating which is liable to superimpose peculiarities of its own upon the spectrum, makes former energy determinations inapplicable to the present case. It is only after the distribution of energy in the spectrum used shall

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[1] *Astrophysical Journal*, **26**, 326, 1907; **27**, 183, 1908.

[2] *Philosophical Magazine*, (6), **7**, 26, 1904.

have been determined that the curves in question may be transformed into true sensibility curves.

In their earlier paper Messrs. Stebbins and Brown compare values of the candle-power of moonlight, determined visually, with those determined by means of the selenium cell, and find that the latter vary among themselves by more than 500 per cent. These differences are satisfactorily accounted for in the later paper, where it is shown that different cells have different sensibility curves. In regard to this work I am of the opinion that no good ground exists for the making of such comparisons of candle-power until it shall have been shown that the sensibility curve of the selenium cell is the same as that of the human eye, and that the integration of the effects of various wave-lengths is the same in both cases. To my knowledge, no work has been done on the latter subject, but as to the former, it is evident that the necessary conditions for comparison are decidedly not fulfilled. In fact, if we were to use a cell which is highly sensitive in the red, and comparatively insensitive in the green and blue, we are liable to make the discovery that a red-hot poker is a better illuminant than a mercury-vapor arc.

With the intention of applying the selenium cell to photometric measurements, some experiments bearing on this subject were begun here—but on account of the illness of the graduate student who collaborated with me, and on account of a lack of time on my part, the work had to be discontinued before it was fairly begun. Nevertheless, we succeeded in convincing ourselves of the feasibility of our undertaking which, briefly, was this: given a cell whose sensibility curve has been accurately determined, to produce a color-screen such that the resultant sensibility curve of selenium cell and color-screen shall be the same as that of the normal human eye for a definite intensity of illumination. Whether or not such an arrangement might be of service in the determination of stellar magnitudes, remains to be seen. The facts in the case are these: there is no difficulty in constructing cells (as I have convinced myself by actual trial) having an effective area varying from less than 1 sq. mm to 20 sq. cm; by the use of extra-focal images, the entire area of the cell may be utilized and by employing a source of high electrical potential together with an Einthoven string-galvanometer[1] (having a sensi-

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[1] *Annalen der Physik*, 21, 483, 1906.

bility of 1×10^{-11} amperes) there is at least a possibility of obtaining useful results. A discussion of the Purkinje effect, integration of various wave-lengths, hysteresis, etc., will follow later in connection with a full account of the work.

In my opinion, the only measurements, carried out by means of the selenium cell, which are warranted at the present time, are those involving a determination of the variations of intensity in the same source of light whose effective area alone changes. Some very excellent results of this character have already been obtained, among which might be mentioned those of Messrs. Stebbins and Brown,[1] on the variations of moonlight during a complete period and those of Ruhmer[2] and others[3] on the variations of light during an eclipse of the sun.

A. H. PFUND

JOHNS HOPKINS UNIVERSITY
May 1908

ON THE TRANSPARENCY OF BORIC ANHYDRIDE

Mr. Fritsch[4] and Mr. Zschimmer[5] have both called attention to the transparency of boric anhydride for ultra-violet light. Mr. Fritsch states that, as far as he could observe in a qualitative way with a quartz spectrograph, B_2O_3 exerted no absorption in the region of short wave-lengths.

In view of these facts it seemed worth while to determine the absorption of this substance in the region of light more refrangible than λ 1850. The experiment was carried on with a vacuum grating spectroscope in the manner previously described by the writer.[6] As a result of the observations it appears that boric anhydride in thicknesses of one or two millimeters is not transparent, for practical purposes, to light of shorter wave-length than λ 1700. This substance is, therefore, of the same order of transparency as purple fluorite.[7] It is less transparent than quartz of the same thickness.

THEODORE LYMAN

JEFFERSON PHYSICAL LABORATORY
HARVARD UNIVERSITY
May 1, 1908

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[1] *Astrophysical Journal*, **26**, 326, 1907.

[2] *Electrotechnische Ztschr.*, **25**, 1025, 1904.

[3] *Physikalische Ztschr.*, **6**, 838, 1905.

[4] *Ibid.*, **8**, 518, August 1, 1907.

[5] *Ibid.*, **8**, 611, September 15, 1907.

[6] *Astrophysical Journal*, **23**, 196, 1906.

[7] *Ibid.*, **25**, 50, 1907.

INVITATION FOR SUBSCRIPTIONS TO THE PHOTOGRAPHIC CHARTS BY JOHANN PALISA AND MAX WOLF

Professor Max Wolf, of Heidelberg, has much facilitated my task of finding and observing small planets, especially those of the faintest magnitudes, by sending me copies of his photographs; so that now it takes me only about one-fourth the time formerly required to find them. This suggested to me the idea that it would be a great advantage if the photographs of the Heidelberg Astrophysical Institute were made available for every observer in a form suitable for immediate use. As Professor Wolf had intended at a later time to collect his photographs and join them in a map, he kindly offered to furnish positives free of cost. On these positives a reseau is then carefully cut, the curvature of the parallels being determined by the stars themselves. Each plate covers 50 square degrees, the scale being 36 mm to the degree. Contact prints are then made from the positives, on smooth but not glossy bromide paper; and the necessary text, including the numbers for right ascension and declination, is then printed on the sheets, which admit of pencil entries and erasures.

So far a series of twenty plates has been provided with graduations, and the prints will be ready by the last of July. This is a private undertaking, and as the cost of the maps must be borne by those who order them, I invite subscriptions. As the paper is the most expensive item, and I cannot risk pecuniary loss, only as many maps will be printed as are subscribed for in advance. If separate sheets are printed later the cost will be somewhat greater.

I have not attached a scale of magnitudes to these maps for two reasons. On account of different exposures, disks of equal size do not represent the same magnitude on different plates, and even on a single plate the scale is not the same at the center and near the edge. On the average the limiting magnitude on the prints is the same as that of the great refractor of the Vienna Observatory; accordingly the maps extend down to the fourteenth magnitude.

The price of the series is seven dollars and a half for the twenty sheets. After December 31, 1908, when the subscription will close, the price will be ten dollars. I request my honored colleagues and the institutions wishing the maps kindly to order them as soon as possible, before December 31 at the latest; and in order to save me trouble, to send the money in advance. In acknowledging the receipt of the maps the purchasers will confer a favor by informing me if they intend to order any further series, as two or three additional series, at the most, might be prepared in the course of a year.

As already mentioned, this undertaking is by Professor Wolf and myself. I alone sign this invitation because I have taken in hand the second part of the work, and will have charge of the list of subscriptions and the delivery of the maps. JOHANN PALISA

OBSERVATORY
TÜRKENSCHANTZSTRASSE 17
VIENNA, AUSTRIA

PHOTOGRAPHIC PRINTS OF THE FIELDS COVERED BY THE HAGEN CHARTS AROUND THE FAINTER VARIABLE STARS

Many of the fields around faint variables had been photographed with the 24-inch reflector of the Yerkes Observatory, and at Father Hagen's request the programme was extended to include all of his charts in Series I, II, III, and VI, in which the variable reaches the thirteenth magnitude or fainter at minimum. Out of the 193 fields in the four series, the variable becomes sufficiently faint in 140 cases. These have been photographed, and negative prints on bromide paper, 8 by 10 inches in size, can be supplied to order during the autumn of 1908 or later. A list of the fields photographed will be furnished on request. The scale of the prints will be 10″ to 1 mm; therefore the field covered will be 0.8 of a degree square. For galactic fields, crowded with stars, prints on double this scale can be supplied. The name of the field, the place for 1900, and the orientation will be marked on the print. The variable itself will be inclosed in a small circle; therefore the Hagen chart will serve as an index, the brighter stars can be identified on his lists, and with the known scale the positions of the fainter stars relative to the variable can be determined.

The plates were taken by Messrs. Parkhurst and Jordan, mostly with an exposure of one hour, and show stars to the sixteenth photographic magnitude, approximately. The price, intended merely to cover the cost, will probably be 25 cents for each print.

Address the SECRETARY OF THE YERKES OBSERVATORY, Williams Bay, Wis.

NOTICE OF GENERAL INDEX

A general index to the first twenty-five volumes of the *Astrophysical Journal*, covering the period of twelve and one-half years from January 1895 to June 1907, has been prepared by Mr. S. B. Barrett, librarian of the Yerkes Observatory. It is arranged both by authors and by subjects, and forms a book of 136 pages, bound in paper, conforming in size and style to the regular volume indices of the *Journal*.

It may be obtained from the University of Chicago Press, at a price of $1.50, postpaid. European subscriptions will be filled through Messrs. William Wesley & Son, 28 Essex Street, Strand, London, England, and future foreign orders should be sent to this address (price 6*s*. 6*d*.). Free copies cannot be supplied, either for periodicals received in exchange for the *Astrophysical Journal*, or otherwise.

THE
ASTROPHYSICAL JOURNAL
AN INTERNATIONAL REVIEW OF SPECTROSCOPY
AND ASTRONOMICAL PHYSICS

VOLUME XXVIII SEPTEMBER 1908 NUMBER 2

JULES CÉSAR JANSSEN

By A. DE LA BAUME PLUVINEL

La carrière scientifique de Janssen a été faite plutôt dans des observatoires temporaires installés dans quelque partie reculée du globe et avec un matériel facilement transportable, que dans des établissements fixes pourvus de grands instruments. C'est que Janssen était, avant tout, un missionnaire de la science, toujours prêt à se dépenser en nouveaux efforts pour organiser et mener à bien une expédition. Son esprit d'entreprise aimait ces voyages où il était soutenu par la pensée de se dévouer plus complètement à la science qu'en travaillant paisiblement dans son laboratoire.

Les principales missions remplies par Janssen avaient pour objet l'observation d'un phénomène visible seulement en un point determiné du globe, ou la recherche d'un ciel favorable à certaines expériences délicates. Mais, dans l'un et l'autre cas, Janssen poursuivait des expériences qui avaient un but commun car son œuvre présente une unité remarquable. On peut dire, en effet, que toutes ses études ont porté sur l'absorption sélective des radiations par les gaz. Sa vocation pour ce genre de recherches a été déterminée par les découvertes de Kirchhoff et Bunsen sur les spectres d'absorption aussi les premières expériences spectroscopiques de Janssen datent-elles de 1862, c'est-à-dire peu de temps après que les physiciens allemands eussent fait connaître leurs travaux.

Janssen a étudié l'absorption des radiations solaires produites par l'atmosphère même du soleil, d'une part, et par l'absorption de notre atmosphère terrestre, d'autre part. C'est en observant les enveloppes gazeuses du soleil, qui sont seulement visibles pendant les courts instants que dure une éclipse totale, qu'il a réalisé la première partie de ce programme, et c'est en entreprenant ses travaux classiques sur les raies telluriques qu'il a réalisé la seconde. Nous allons suivre Janssen dans ses recherches sur ces deux ordres de questions.

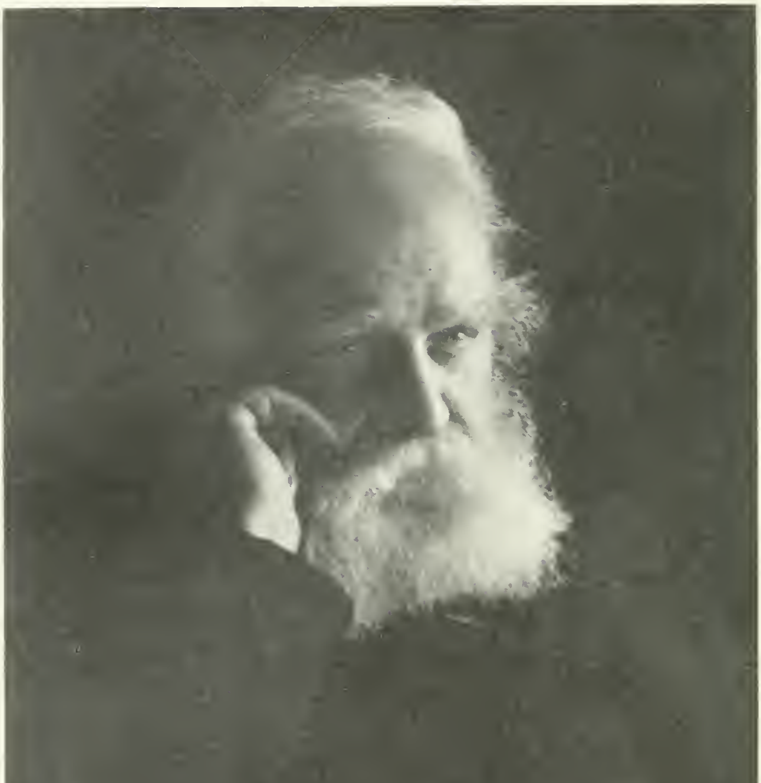
L'éclipse totale du soleil de 1868 était impatiemment attendue par Janssen, car elle allait lui fournir l'occasion d'étudier, pour la première fois, au spectroscope, les atmosphères solaires. Pour se préparer, en quelque sorte, à l'observation de cet important phénomène, Janssen demanda à être envoyé à Trami, en Italie, pour observer l'éclipse annulaire du soleil de 1867. Son but était d'étudier le spectre de l'anneau solaire, pour y découvrir, si possible, des traces de l'absorption produite par l'atmosphère solaire. Mais le spectre de l'anneau se montra identique au spectre du centre du soleil.

Pendant la même éclipse, il a cherché aussi à voir la couronne, sans pouvoir y parvenir.

Mais l'éclipse de 1868 lui réservait l'honneur de faire une grande découverte. On sait qu'après avoir vu, dans son spectroscope, les raies brillantes des protubérances qui apparurent pendant la totalité, il n'hésita pas à affirmer, avec l'autorité que lui donnait sa grande compétence en spectroscopie, qu'il pourrait revoir ces raies en dehors des éclipses. Dès le lendemain de l'éclipse, il eut la joie de voir se réaliser ses prévisions.

On sait aussi que la même découverte fut faite indépendamment en Angleterre, par Sir Norman Lockyer, aussi les noms de ces deux savants sont-ils demeurés associés à cette application si féconde de l'analyse spectrale. Janssen paraît avoir entrevu, dès le premier jour, toute l'importance de la découverte qu'il venait de faire. On en trouve la preuve dans une lettre qu'il adressait à sa mère et où il dit: "Je lis dans un livre jusqu'ici fermé à tous et dans lequel on ne pouvait jeter que quelques courts regards pendant les éclipses."

Les résultats obtenus pendant l'éclipse de 1868, étaient trop beaux pour que Janssen se soit arrêté dans la voie qu'il venait d'ouvrir aux astronomes. Aussi avait-il décidé d'aller en Algérie à l'occasion



JULES CÉSAR JANSSEN

de l'éclipse totale du mois de décembre 1870. Cette éclipse ne put malheureusement pas être observée à cause du mauvais temps, mais elle fournit à Janssen l'occasion de donner à la science un témoignage éclatant de dévouement. Enfermé, en effet, dans Paris par le siège, Janssen ne craignit pas d'affronter les risques d'un voyage en ballon pour franchir les lignes ennemies. Cet acte de courage fit plus pour sa popularité que sa belle découverte du spectre des protubérances, et, pour le public, qui voyait encore à cette époque un vrai danger à affronter la route des airs, cette manière audacieuse de s'échapper de la capitale assiégée, donna la mesure du dévouement dont Janssen était capable pour la science. Janssen garda de ce voyage aérien exécuté dans de si périlleuses conditions, un amour sincère pour l'aérostation. Il eut souvent l'occasion de prouver l'intérêt qu'il portait à cette science en donnant de précieux conseils aux aéronautes, en acceptant de présider diverses sociétés aéronautiques et en donnant une large hospitalité, à Meudon, à des congrès internationaux d'aérostation.

Un an après l'éclipse de 1870, une autre éclipse devait être visible aux Indes et à Java. Janssen n'eut garde de manquer cette nouvelle occasion d'étudier les atmosphères solaires. Un examen attentif des conditions météorologiques des diverses localités visitées par l'éclipse lui fit adopter une station située aux Indes, dans les Neelgheries; les évènements lui donnèrent raison, car il aurait été difficile d'observer l'éclipse dans de meilleures conditions atmosphériques. Cette fois l'attention de Janssen se porta principalement sur la couronne. Il observa, dans le spectre de la couronne, non seulement la raie verte, dont la présence avait déjà été signalée, mais aussi les raies noires du spectre solaire démontrant ainsi qu'une partie de la lumière de la couronne est de la lumière solaire réfléchie, ce qui tend à prouver que l'atmosphère coronale n'est pas exclusivement gazeuse, mais comprend aussi des particules solides ou liquides.

En 1875, nous retrouvons Janssen observant une éclipse dans la presqu'île de Malacca au retour d'un voyage au Japon.

Puis, en 1883, sans craindre les fatigues d'un voyage fait dans des conditions pénibles, il se rend à l'île Caroline, en plein océan Pacifique, pour observer une éclipse totale de soleil, remarquable par sa grande durée. Grâce aux plaques photographiques au gelatino-bromure d'argent, qui venaient d'être inventées, le phénomène put être photographié dans des conditions très variées, ce qui lui permit de rapporter des documents du plus haut intérêt au sujet de l'étendue de la couronne solaire.

Avant de terminer sa carrière, Janssen voulut encore observer une dernière fois un de ces beaux phénomènes qui eurent toujours pour lui tant d'attrait. Aussi, en 1905, malgré son âge avancé, il se rendit en Espagne, pour se donner le plaisir de contempler une éclipse en curieux plutôt que de l'observer en astronome.

Nous venons de voir ce qu'a fait Janssen pour l'étude des enveloppes gazeuses du soleil par l'application du spectroscope à l'observation des éclipses. Nous allons passer en revue maintenant ce qu'il a fait pour l'étude de l'absorption des radiations solaires par notre propre atmosphère.

Les premières expériences spectroscopiques de Janssen se rapportent à l'étude des bandes noires qui apparaissent dans le spectre du soleil à l'horizon et qui avaient été signalées par Sir David Brewster, sans que ce dernier ait reconnu leur véritable structure et la cause de leur formation. Par des observations faites à Rome en 1862-1863, Janssen découvrit que les bandes de Brewster étaient résolubles en raies, et il prouva que l'origine de ces raies devait être attribuée à l'absorption sélective des rayons solaires produites par les gaz de notre atmosphère. On reconnut plus tard que c'était l'oxygène de l'atmosphère qui donnait naissance à ces raies A, *a*, et B du spectre solaire. Mais l'oxygène de notre atmosphère n'est peut-être pas la seule cause de la production de ces raies; s'il existe, en effet, de l'oxygène dans les enveloppes gazeuses du soleil, l'atmosphère solaire pourrait aussi avoir sa part dans la production du phénomène. Or, au point de vue de la théorie du soleil, il est de la plus haute importance de savoir si l'oxygène coexiste avec l'hydrogène dans l'atmosphère solaire. Janssen attachait à cette question de la présence de l'oxygène dans le soleil une importance capitale. Aussi, a-t-il cherché, par toutes les manières possibles, à décider si les raies A, *a*, B du spectre solaire ont une origine à la fois terrestre et solaire ou si elles sont produites uniquement par notre atmosphère. Pour résoudre ce problème, il produisit dans son laboratoire ces raies d'absorption pour se rendre compte si une colonne d'oxygène équivalente à l'oxygène contenu dans notre atmosphère pouvait produire des raies de même intensité que celles que nous observons dans le spectre solaire. Dans le même ordre d'idées, il observa le spectre d'une source lumineuse assez distante pour que l'air interposé puisse produire une absorption équivalente à celle de l'atmosphère tout entière aux différentes hauteurs du soleil au-dessus de l'horizon. Puis, nous le verrons faire en quelque sorte la contre expérience et chercher si, en diminuant suffisamment l'action absorbante de l'air interposé, il parviendrait à faire disparaître les raies en question.

L'étude des spectres d'absorption des gaz a fait l'objet de recherches trés approfondies de la part de Janssen. Il examinait, au spectroscope, la lumière d'une source à spectre continu qui avait traversé des tubes contenant des gaz sous diverses pressions et à diverses températures. Son laboratoire, installé dans les anciennes écuries du château de Meudon, lui permettait de disposer de tubes dont la longueur atteignait 60 mètres. Les expériences ont surtout porté sur l'oxygène. En faisant varier la pression du gaz dans le tube, il faisait apparaître à volonté les raies d'absorption de l'oxygène et notamment la raie B. Ces expériences montrèrent qu'une certaine raie d'absorption, B par example, apparaissait toujours lorsque le produit de la longueur du tube par la pression du gaz atteignait la même valeur.

Mais ces expériences sur les raies d'absorption de l'oxygène, ont conduit Janssen à une observation remarquable qui demanderait à être répétée avec les moyens perfectionnés dont dispose la physique moderne. Janssen découvrit, qu'en outre des raies telluriques, le spectre d'absorption de l'oxygène présentait, dans certaines conditions, un système de bandes difficiles à résoudre en raies et dont la production est régie par une toute autre loi que celle que nous avons indiqué plus haut pour les raies telluriques. Ces bandes font leur apparition lorsque le produit de la longueur du tube par le carré de la pression, atteint une certaine valeur. Cette loi trouva une éclatante confirmation, lorsque M. Olszewski étudia le spectre d'absorption de l'oxygène liquide. Il reconnut que les bandes de Janssen apparaissaient lorsque la couche de l'oxygène absorbante atteignait l'épaisseur indiquée par la loi du carré des pressions.

Janssen a aussi confirmé sa loi d'une autre manière: il a calculé que, lorsque le soleil était à une hauteur au-dessus de l'horizon inférieur à 4°, l'épaisseur de la couche d'air traversée par les rayons solaires était suffisante pour donner naissance aux bandes. Or, s'étant rendu dans le Sahara, afin de pouvoir observer le soleil à son lever, Janssen reconnut la présence des bandes dans le spectre solaire, tant que le soleil n'avait pas atteint précisément cette hauteur de 4°.

Ces résultats remarquables peuvent avoir pour la physique moléculaire des conséquences théoriques dont l'importance ne paraît pas avoir été suffisamment appréciée jusqu'ici.

Dans ses expériences de laboratoire à Meudon, Janssen ne se contenta pas de faire varier la pression des gaz et la longueur des colonnes traversées par la lumière; il porta aussi les gaz à des températures élevées afin de se rapprocher des conditions où ils se trouvent dans le soleil. Par des procédés électriques, très remarquables pour l'époque où ils ont été imaginés, Janssen a pu porter des gaz à des températures atteignant 900° C. Aucun phénomène nouveau ne s'est manifesté à cette température, mais la visibilité des raies d'absorption avait considérablement augmentée.

L'absorption produite par la vapeur d'eau fut aussi étudiée dans le laboratoire de Meudon. Déjà, à l'origine de ses études de spectroscopie, en 1867, Janssen avait observé le spectre d'absorption de la vapeur d'eau en faisant passer des rayons lumineux au travers d'un tube de 37 mètres de long rempli de vapeurs. Cette mémorable expérience faite à l'usine à gaz de la Villette, avait permis à Janssen de relever les positions des principales raies d'absorption de la vapeur d'eau. Mais ces expériences furent reprises dans de meilleures conditions, avec des instruments perfectionnés, dans le laboratoire de Meudon, en 1887.

L'étude du spectre de la vapeur d'eau avait pour but de rechercher si l'eau existe dans les atmosphères des planètes. Cette question, d'une importance capitale pour l'astronomie physique, a toujours beaucoup préoccupé Janssen. Dès 1867, sur l'Etna, et en 1869 sur l'Himalaya, Janssen avait observé le spectre de Mars pour chercher à y reconnaître les raies *a* de la vapeur d'eau. A cet effet, il avait comparé l'intensité des raies *a* dans le spectre de Mars et dans le spectre de la lune, ces deux astres étant à la même hauteur au-dessus de l'horizon. Janssen avait conclu de ses observations que le spectre de Mars donnait des signes évidents de la présence de la vapeur d'eau dans l'atmosphère de la planète et il considérait ses expériences comme assez décisives pour maintenir ses conclusions, lorsqu'en 1895, Campbell annonça que les grands instruments de l'Observatoire de Lick ne lui avaient pas permis de trouver des traces de vapeur d'eau sur Mars. Or, tout dernièrement, Mr. Slipher de l'Observatoire Lowell a obtenu des photographies sur lesquelles les raies de la vapeur d'eau paraissent plus intenses dans le spectre de Mars que dans le spectre de la lune. Cette observation importante vient confirmer, en tous points, les conclusions de Janssen.

Mais revenons aux expériences de Janssen sur l'oxygène. Après avoir étudié, dans son laboratoire, les conditions de la production des bandes d'absorption de l'oxygène, Janssen voulut obtenir ces bandes en interposant, entre la source lumineuse et l'observateur, une couche d'air suffisante pour leur donner naissance. Or, en 1889, la Tour Eiffel venait d'être construite et un puissant phare électrique établi sur son sommet pouvait être dirigé vers l'observatoire de Meudon. De plus, la distance qui séparait la tour de l'observatoire étant de 7.7 kilomètres, la lumière, avant d'arriver à l'observateur, avait à traverser une colonne d'air précisément équivalente, au point de vue de l'absorption, à notre propre atmosphère. Dans ces conditions, les raies d'absorption de l'oxygène apparaissaient avec la même intensité que dans le spectre solaire, ce qui apportait une confirmation de l'origine exclusivement terrestre de ces raies.

Cette expérience de la Tour Eiffel pouvait être considérée comme la répétition d'une autre expérience ingénieuse réalisée par Janssen, dès 1864, sur les bords du lac de Genève. Un feu de bois fut allumé à Nyon, sur l'une des rives du lac; or, tandis qu'à une faible distance le spectre de ce foyer était continu, il présentait, lorsqu'on l'observait de Gènêve, à une distance de 21 kilomètres, les raies telluriques et de la vapeur d'eau.

Nous avons déjà dit que Janssen, non content d'avoir pu produire artificiellement, en quelque sorte, les raies d'absorption de l'oxygène, avait voulu faire la contre expérience, et s'assurer que les raies telluriques du spectre solaire tendaient bien à disparaître lorsqu'on s'élevait dans l'atmosphère, c'est-à-dire au fur et à mesure que diminue la couche d'air interposée entre le soleil et l'observateur. C'est pour constater ce fait que Janssen entreprit plusieurs ascensions en montagne: au Faulhorn, d'abord, en 1864, puis au Pic du Midi, et plus récemment enfin, au Mont Blanc. Dans une première ascension aux Grands Mulets, en 1888, il constata nettement que les raies du groupe B étaient moins intenses à une altitude de 3,000 mètres qu'elles ne le sont à Meudon, et dans des ascensions au sommet, en 1893 et en 1895, il crut voir que les derniers doublets de B disparaissent complètement. Sa claudication l'empêchant de marcher, il dut pour atteindre le sommet du Mont Blanc, se faire porter sur une sorte de brancard, ou se faire traîner dans un traîneau, ce qui a rendu ces ascensions singulièrement difficiles. Janssen rapporta de ses expéditions au Mont Blanc la conviction qu'un observatoire, construit au sommet même de la célèbre montagne, rendrait certainement d'importants services à la science et contribuerait à résoudre bien des problèmes d'astronomie, de météorologie et de physiologie. L'astronome, en s'élevant à ces altitudes, s'affranchirait de ce que l'on a appelé "la vase atmosphérique," et la lumière des astres lui parviendrait moins déviée et moins diffusée; le météorologiste, placé au sein même de l'atmosphère, surprendrait les secrets de la formation des nuages; le physiologiste enfin pourrait étudier dans ce laboratoire élevé les conditions de la vie sous une pression moitié moindre que dans la plaine.

La création de l'Observatoire du Mont Blanc une fois décidée, il a fallu à Janssen une énergie peu commune pour mener à bien son projet. Grâce à sa parole convaincante, il réussit à réunir les fonds nécessaires pour la construction de l'édifice, puis, bravant les critiques, il posa hardiment la construction sur la neige, au sommet même du Mont Blanc, pour dominer, de cette position culminante, tout le massif des Alpes. C'est peut-être dans cette entreprise de la création de l'Observatoire du Mont Blanc que Janssen donna le mieux la mesure de l'énergie, de la ténacité et de l'audace dont il était capable. N'est-ce pas, d'ailleurs, à propos de la réalisation de cette œuvre qu'il a dit: "J'ai toujours pensé qu'il n'est bien peu de difficultés qui ne puissent être surmontées par une volonté forte et une étude suffisamment approfondie." Dans les dernières années de sa vie, Janssen avait pour l'Observatoire du Mont Blanc, la sollicitude d'un père pour son enfant. Chaque année il se plaisait à donner des conseils aux observateurs qui se proposaient de faire l'ascension du géant des Alpes pour entreprendre quelque recherche nouvelle; il organisait les expéditions dans les moindres détails aidé dans cette tâche par Madame et Mademoiselle Janssen.

Janssen était un enthousiaste de la montagne, il ne cessait de louer ses bienfaits et se plaisait de répéter aux ascensionnistes, cette phrase de notre grand physicien Foucault, "la montagne fait l'homme, la ville le consomme."

Nous venons de voir par quel enchaînement d'idées Janssen a été conduit à observer des éclipses de soleil, à faire des expériences de laboratoire, et à analyser la lumière solaire dans de hautes stations, pour étudier l'absorption produite par les enveloppes gazeuses du soleil et par notre propre atmosphère. En dehors de ces études, Janssen s'intéressa à d'autres questions qui lui offrirent l'occasion de satisfaire ses goûts pour les voyages. En 1874 et 1882, il fut le chef tout indiqué de missions envoyées par la France pour observer les passages de Vénus sur le soleil. C'est pour étudier ces phénomènes qu'il imagina le révolver photographique. Cet instrument permettait de prendre une série de photographies à de courts intervalles afin de décider à quel instant précis avaient lieu les contacts de la planète avec le disque solaire. Le révolver photographique a été le précurseur des appareils de M. Marey pour l'étude des mouvements des animaux et c'est aussi sur son principe que sont construits les cinématographes actuels.

L'étude des volcans, et notamment l'analyse spectrale des gaz qui s'échappent de leurs cratères, attira l'attention de Janssen et fut l'occasion de voyages au Santorin, aux Açores, aux îles Sandwich et tout dernièrement encore au Vésuve.

Enfin, il profita souvent de ses voyages pour déterminer les éléments magnétiques du globe. C'est ainsi que son premier voyage scientifique a eu pour objet de reconnaître la position de l'équateur magnétique au Pérou; il fit ensuite, aux Açores, des observations magnétiques appliquées à la géologie et on lui doit aussi des déterminations de l'équateur magnétique aux Indes et dans la presqu'île de Malacca.

Mais ses nombreux voyages ne suffisaient pas à absorber toute son énergie. Entre temps, il fonda, en 1874, l'observatoire de Meudon, et, en outre de ses travaux sur les spectres d'absorption des gaz, dont nous avons parlé, il s'y occupa de photographie et notamment de photographie solaire. Janssen a été un des premiers à pressentir les services que pourrait rendre la plaque sensible, dans les observatoires et il résuma d'un mot le rôle prépondérant que la photographie était appelée à jouer dans les sciences d'observation en disant que la plaque photographique était la véritable rétine du savant.

Aidé de M. Arents, d'abord, puis par M. Pasteur, il obtint, dans son observatoire de Meudon, cette remarquable série de photographies solaires dont les épreuves les plus caractéristiques ont été réunies dans un atlas et constituent un véritable monument élevé à l'histoire du soleil. Ces photographies faites spécialement en vue de l'étude physique de la surface solaire, présentent les détails les plus délicats de la photosphère. En les examinant attentivement, Janssen a découvert que la surface du soleil présente une texture particulière qu'il a désignée sous le nom de réseau photosphérique. La production de ce réseau fut attribuée tout d'abord à des déplacements réels des granulations de la photosphère, mais on se demanda plus tard si l'on ne devait pas en chercher l'origine dans des réfractions irrégulières produites soit par notre atmosphère, soit par l'atmosphère du soleil.

La photographie a toujours été en honneur à l'observatoire de Meudon, et, non content de l'appliquer à des observations qualitatives, Janssen voulut s'en servir pour faire des observations quantitatives. Aussi lui doit-on de nombreuses expériences de photométrie photographique, et notamment des déterminations des éclats relatifs du soleil et des étoiles. Il a été un des premiers à faire usage, pour des mesures photométriques, de disques stellaires obtenus en dehors du foyer. Mais Janssen avait, pour la photographie, une prédilection qui s'étendait à toutes les applications de cette science et il en donna la preuve en acceptant de présider de nombreuses réunions de sociétés et de congrès photographiques.

Janssen était, avant tout, un observateur et un homme d'action. Il ne s'est pas laissé tenter par le désir de donner son nom à une théorie du soleil; il savait qu'il est plus utile de récolter des observations que d'édifier des théories sur des faits insuffisamment démontrés. Mais il ne faudrait pas en conclure que l'esprit de Janssen restait indifférent aux spéculations. Dans nombre de ses écrits on trouve une élévation de pensées qui témoigne de son esprit philosophique et de son souci de remonter à l'origine des choses.

Né en 1824, Janssen ne s'adonna complètement à la science que vers 1860 à l'âge de 36 ans, mais sa carrière scientifique fut néanmoins aussi longue que celle de bien des savants, car il conserva tard toutes ses aptitudes pour le travail et s'éteignit le 23 décembre dernier, après avoir atteint sa 84^{e} année.

SOLAR VORTICES[1]

By GEORGE E. HALE

The problem of interpreting the complex solar phenomena recorded by the spectroheliograph has occupied my attention since the first work with this instrument in 1892. The measurement of the daily motions in longitude of the calcium flocculi has led to several new determinations of the solar rotation,[2] and their areas, measured by a photometric method, are being used as an index to the solar activity. Various investigations on their forms at different levels,[3] their distribution in latitude and longitude, etc., have also been carried out. But the failure of the calcium flocculi to indicate the existence of definite currents in the solar atmosphere has been a disappointment.

The hydrogen flocculi, though occupying the same general regions on the sun's disk, are distinguished from those of calcium by several striking peculiarities. In the first place, most of them are dark, while the corresponding calcium (H_2) flocculi are bright. Secondly, as I have recently shown,[4] they seem to obey a different law of rotation, in which the equatorial acceleration (better, the polar retardation), shared by the spots, faculae, and calcium flocculi, does not appear. A third peculiarity, briefly mentioned in previous papers, is clearly visible on many hydrogen photographs. It is a decided definiteness of structure, indicated by radial or curving lines, or by some such distribution of the minor flocculi as iron filings present in a magnetic field (see, for example, *Astrophysical Journal*, Vol. XIX, Plates X and XII). First recognized at the beginning of our work with the hydrogen lines in 1903, this suggestive structure has repeatedly shown itself on the Mount Wilson negatives. But its

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 26.

[2] Hale and Fox, *The Rotation of the Sun, as Determined from the Motions of the Calcium Flocculi*. Carnegie Institution (in press); Fox, *Science*, April 19, 1907; Hale, *Contributions from the Mount Wilson Solar Observatory*, No. 25; *Astrophysical Journal*, 27, 219, 1908.

[3] Hale and Ellerman, *Publications of the Yerkes Observatory*, Vol. III, Part I.

[4] Hale, *Contributions from the Mount Wilson Solar Observatory*, No. 25; *Astrophysical Journal*, 27, 219, 1908.

true meaning did not appear until the results described in this paper had been obtained.

With the Rumford spectroheliograph the hydrogen lines $H\beta$, $H\gamma$, and $H\delta$ were used. Certain differences between the photographs, which seemed to depend upon the wave-length, pointed to the desirability of trying $H\alpha$. But plates sufficiently sensitive to red light were not to be had at that time, and therefore the experiment was postponed.

The extreme sensitiveness in the red of plates prepared according to a formula due to Wallace[1] now renders it a simple matter to photograph the sun with $H\alpha$. Some preliminary work with the spectroheliograph attachment of the 30-foot Littrow spectrograph of the tower telescope, in which I had the assistance of Mr. Adams, indicated that bright flocculi are more numerous and extensive when photographed with $H\alpha$ than when $H\delta$ is used. I then tried $H\alpha$ with the five-foot spectroheliograph of the Snow telescope, and immediately obtained excellent results. The images were stronger and of much better contrast than those given by $H\delta$. Moreover, the curved and radial structure surrounding sun-spots was so striking as to lead to the hope that important advances might be expected to follow from the systematic use of the $H\alpha$ line.

On account of the difference in curvature of $H\alpha$ and $H\delta$, these preliminary photographs made with $H\delta$ slits showed only a very narrow zone of the solar image. A new pair of slits, of suitable curvature for $H\alpha$, was accordingly made for the five-foot spectroheliograph, and as soon as these were ready I completed the adjustments of the instrument, with Mr. Ellerman's assistance, and made comparative photographs of the entire disk with $H\alpha$ and $H\delta$. The differences exhibited by these plates are very marked. For example, a long dark flocculus, strongly shown by $H\alpha$, is represented on an $H\delta$ photograph by only a few of its most intense parts. In the case of bright flocculi, the differences are even more conspicuous, large luminous areas shown by $H\alpha$ being absent from the $H\delta$ plates. To eliminate errors arising from possible changes on the sun between exposures, the photographs were taken in rapid succession, an $H\alpha$ plate between two of $H\delta$. In this way all doubts as to the genuine-

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[1] *Astrophysical Journal*, 26, 299, 1907.

ness of the observed differences were removed. Plate III illustrates the general character of these differences, concerning the cause of which we may now inquire.

It naturally occurred to me that photographs of a prominence at the sun's limb, taken with the various hydrogen lines, would be likely to throw light on the question. Mr. Ellerman accordingly made a series of photographs of a prominence, using the lines $H\alpha$, $H\beta$, $H\gamma$, and $H\delta$. The fall of intensity toward the violet was very marked, the faint $H\delta$ image bringing out only the brightest parts of the prominence as photographed with $H\alpha$ (Figs. 2 and 3, Plate IV). $H\beta$ and $H\gamma$ gave intermediate results, resembling those obtained with $H\delta$.

It thus seems probable that the marked intensity of the $H\alpha$ flocculi results from the great strength of the $H\alpha$ line in the chromosphere and prominences. $H\delta$ is strong enough in the middle and sometimes in the upper chromosphere and in the lower parts of bright prominences to show the hydrogen in these regions when projected on the disk. $H\alpha$, being much more intense, renders visible a higher region of the solar atmosphere, including the upper chromosphere and bright prominences. Whether these are to appear as bright or dark flocculi, when photographed against the disk, probably depends primarily upon their temperature, though the conditions may not be such as to permit the direct application of Kirchhoff's law.

But the photographs bring out a second fact of interest. Although, as has been stated, the flocculi are generally stronger on the $H\alpha$ plates, it cannot be said that these $H\alpha$ images are merely intensified $H\delta$ images. For there is an important point of difference: dark $H\delta$ flocculi are sometimes replaced on the $H\alpha$ plates by bright flocculi or by apparently neutral spaces. The condition of the hydrogen in such regions thus appears to be the same as in certain stars, whose spectra show $H\alpha$ bright and the more refrangible hydrogen lines dark.[1]

The importance of continuing the work of photographing the sun

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[1] I leave for future consideration the question whether the neutral regions on the $H\alpha$ plates are to be regarded as bright flocculi of reduced intensity. It will also be important to determine whether Kayser's explanation of the appearance in a stellar spectrum of both bright and dark hydrogen lines (*Astrophysical Journal*, 14, 313) will apply to solar phenomena.

PLATE III

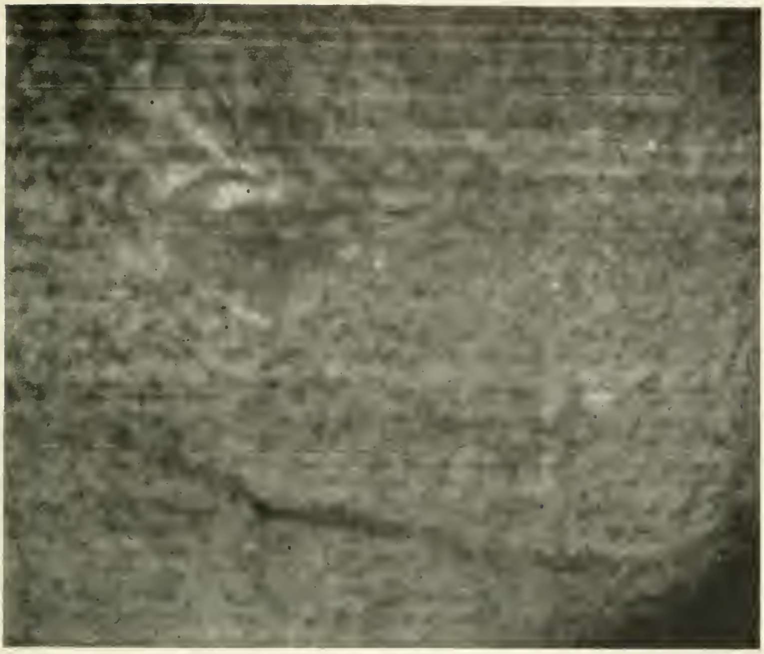
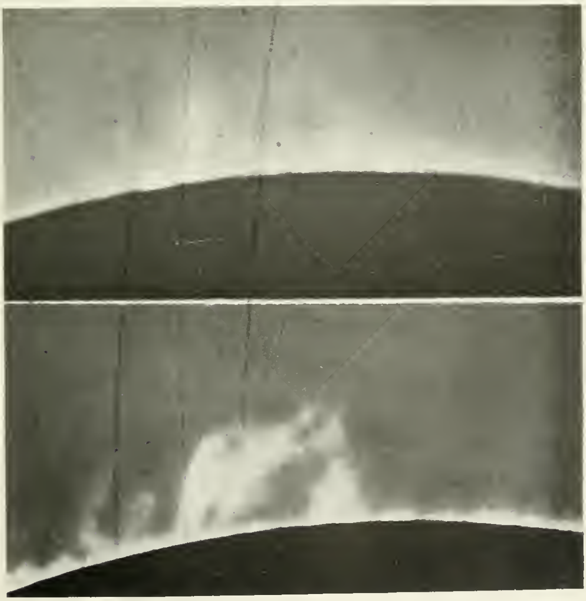


Fig. 1.—Hydrogen Flocculi, Photographed with the *Hα* Line
1908, May 1, $4^h\ 48^m$ p. m. Scale. Sun's Diameter = 0.2 Meter

Fig. 2.—Hydrogen Flocculi, Photographed with the *Hδ* Line
1908, May 1, $5^h\ 07^m$ p. m. Scale: Sun's Diameter = 0.2 Meter

PLATE IV

Fig. 1.—Prominences at Eastern Limb of the Sun
1908, May 26, $6^h\ 38^m$ A. M. Scale: Sun's Diameter = 0.3 Meter



Figs. 2 and 3.—Prominences Photographed with $H\delta$ (Fig. 2) and $H\alpha$ (Fig. 3)
1908, April 3. Scale: Sun's Diameter = 0.3 Meter

with $H\alpha$ was obvious, and I immediately modified the daily programme of observations with this object in view. In the photography of the chromosphere and prominences at the limb, $H\alpha$ was substituted for the H line of calcium, since it was found to give stronger and sharper negatives. For the disk $H\alpha$ was adopted in place of $H\delta$, though work was continued with the latter line long enough to secure a series of comparative photographs. Later, as more $H\alpha$ plates were needed, the daily series of photographs with the iron line λ 4046 was discontinued, and all of the observing time of the Snow telescope in the morning devoted to $H\alpha$ work.[1] In the afternoon this line is also used most of the time, though one plate is made with H_1 and one with H_2 of calcium.

A serious difficulty at once presented itself. Previously only a few photographs had been taken during each of the best observing periods, which last less than two hours in the early morning and late afternoon. Between exposures the mirrors were shielded from sunlight, and electric fans kept a continuous blast of air directed upon them. Even with these precautions there would frequently be a marked change of focal length during an exposure lasting four minutes. The distortion of the mirrors increased during the observations and strong evidences of astigmatism often appeared before they were completed. Except for occasional eruptions, the calcium, iron, and $H\delta$ flocculi change rather slowly in form, and one or two photographs taken daily with each line sufficed for the investigations in progress. In the case of $H\alpha$ it seemed probable that many photographs, separated by short time-intervals, would be needed to register the phases of rapidly changing phenomena. This would mean almost uninterrupted exposure of the mirrors to sunlight, and such serious distortion that the astigmatism would ruin the photographs.

At this point experience with the tower telescope came in to good advantage. The very thick mirrors used with this instrument are not appreciably distorted in sunlight.[2] Hence it seemed probable that by reducing the aperture of the Snow telescope mirrors the increase in their relative thickness would relieve the difficulty. I

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[1] Except the short interval required to obtain a direct photograph.

[2] Hale, *Contributions from the Mount Wilson Solar Observatory*, No. 23; *Astrophysical Journal*, 27, 204, 1908.

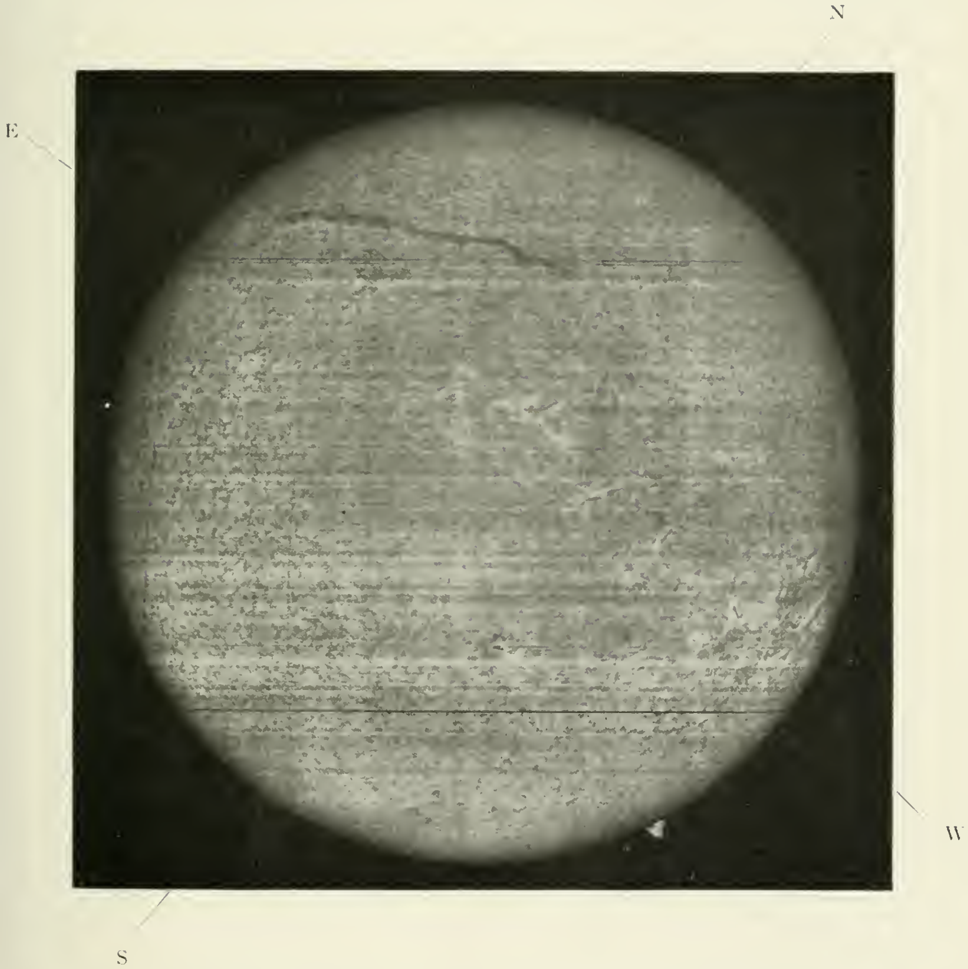
therefore commenced a series of experiments with different apertures, and finally adopted a 15-inch (38 cm) diaphragm for the coelostat in place of the full aperture of 30 inches (76 cm). With this the focal length does not ordinarily change perceptibly during a single exposure. When the mirrors are in sunlight, with very brief interruptions, during a period of an hour, the focal length gradually increases, but the effect of astigmatism is hardly appreciable.

In the work with $H\delta$, the hydrogen flocculi could not be photographed with sufficient contrast unless the very slow "Process" plates (also used for H_1 and H_2) were employed. These plates gave excellent results with $H\alpha$, but could not be used after the aperture had been reduced to 15 inches without undue increase of exposure time. Hence it was necessary to substitute for them Seed's "Gilt Edge" plates, which fortunately serve very well with this line. The first experiments with $H\alpha$ were made about the middle of March. On March 28 the new slits were in place, and the first photographs of the entire disk were obtained. During April the weather was not very favorable, but on April 29 and 30 Mr. Ellerman, then in charge of the routine work with the five-foot spectroheliograph, secured some remarkably fine negatives. The one taken on April 30 is reproduced in Plate V. Apart from the whirls, which may be seen to better advantage in Plates VI and VII, this photograph shows in projection an enormous prominence in the southern hemisphere. This also appears, though much less satisfactorily, on the $H\alpha$ photograph of May 1, and may be traced on the $H\delta$ photograph of the same date (Plate III).

But in spite of its great intensity and length, this prominence is of minor interest in comparison with the structure shown in Plates VI and VII. This is so definite in form and so unmistakable in character as to satisfy the hopes aroused by the earlier photographs. It seems evident, on mere inspection of these photographs, that sun-spots are centers of attraction, drawing toward them the hydrogen of the solar atmosphere. Moreover, the clearly defined whirls point to the existence of cyclonic storms or vortices.

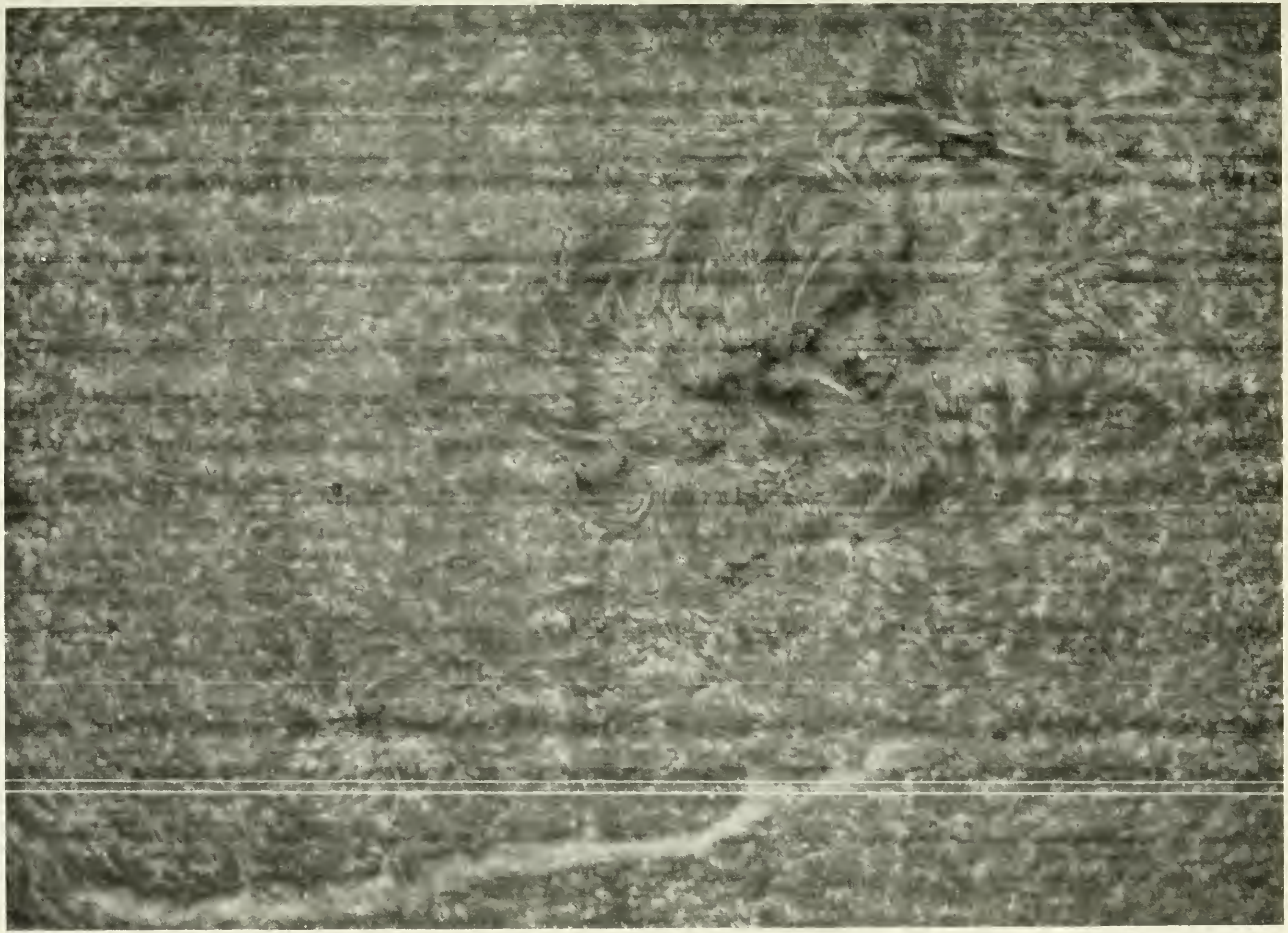
The most striking of these storms occupies an enormous area in the southern hemisphere, extending from the equator to about 35°

PLATE V



THE SUN, SHOWING THE HYDROGEN ($H\alpha$) FLOCCULI
1908, April 30, 5h 06m P. M.

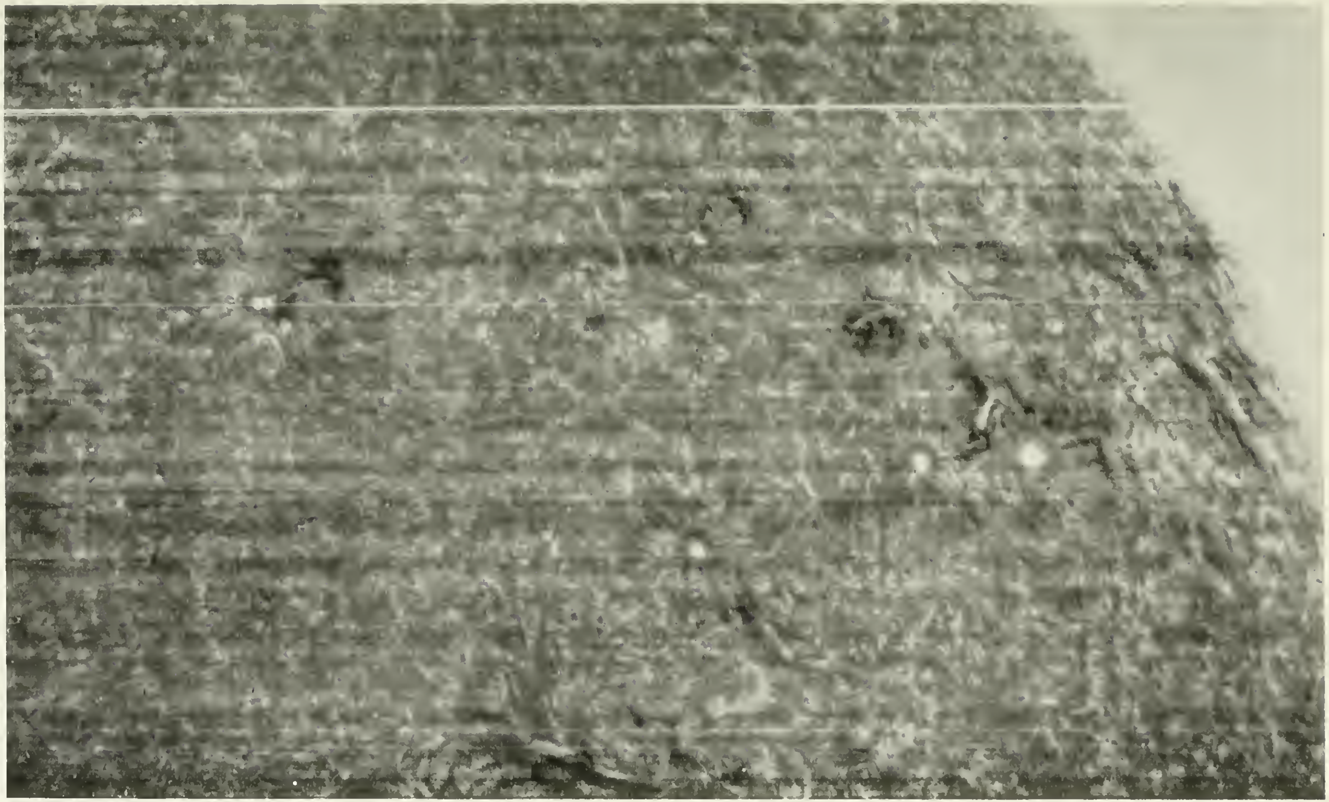
PLATE VI



Hydrogen ($H\alpha$) Flocculi

1908, April 30, $5^h\ 06^m$ P. M. Large scale *negative* print showing portion of Plate V, reversed east and west. Scale: Sun's Diameter = 0.3 Meter

PLATE VII

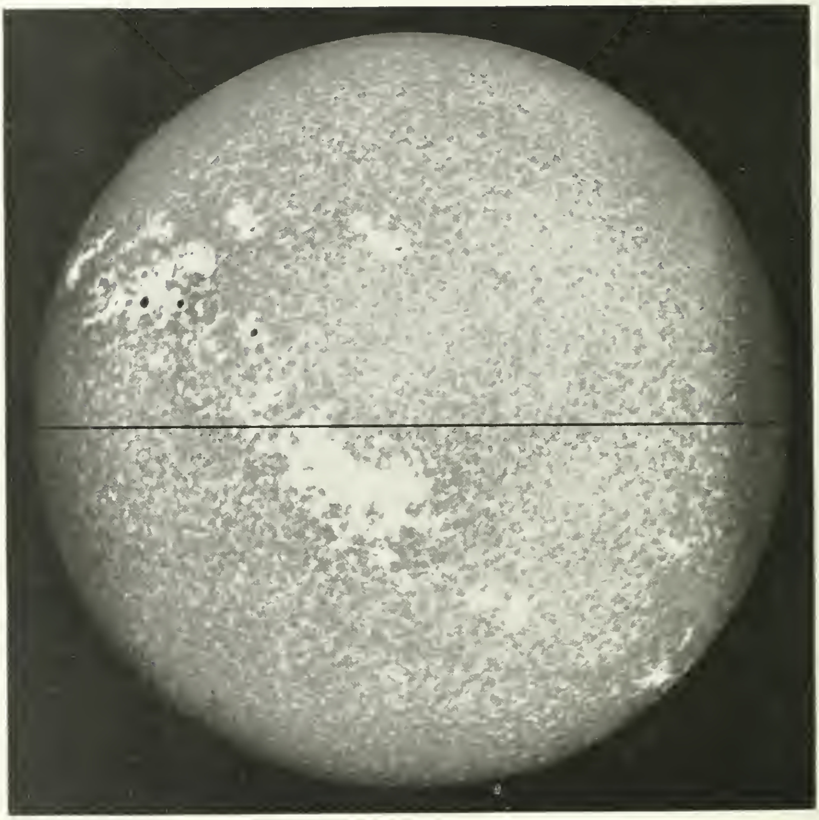


HYDROGEN ($H\alpha$) FLOCCULI SURROUNDING SUN-SPOTS
1908, April 30, $5^h\,06^m$ P. M. Large scale *negative* print showing portion of Plate V, reversed east and west
Scale: Sun's Diameter = 0.3 Meter

PLATE VIII

Direct Photograph of the Sun
1908, April 30, 6h 25m a. m.

PLATE IX



THE SUN, SHOWING THE CALCIUM (H_2) FLOCCULI
1908, April 30, $4^h 43^m$ P. M.

south latitude and about 50° in length. Near the center of this region, partly covered by clouds of bright hydrogen, lies the small spot-group shown (from a direct photograph) in Plate VIII. The corresponding H_2 photograph reveals a large calcium flocculus over the spot-group (Plate IX), but this, though of great size, appears to differ in no essential particular from ordinary calcium flocculi, and gives no evidence of gyratory motion.

A good $H\alpha$ photograph was obtained on April 29, but it was badly stained in the sensitizing process, and many of the flocculi are hidden by streaks on the negative. Fortunately, the greater part of the large storm area is fairly well shown, so that comparisons with the afternoon photograph of April 30 may be made in the stereo-comparator (using the monocular attachment). On account of the changes in form of the flocculi during this interval, the identification of objects suitable for measurement is very difficult and uncertain. Three independent determinations of the positions of certain flocculi on the two plates have been made by Miss Ware. The objects identified on both dates were marked by small dots of ink on the glass side of the negative, and their latitude and longitude measured with the heliomicrometer. When reduced to the same epoch (using for the value of the daily angular motion $\xi = 14^\circ\!.5$, derived from the measurement of 828 points on 35 $H\delta$ plates), the plotted results seem to show the existence of a gyratory motion, in a direction opposite to that of the hands of a watch (north, east, south, west). Although most of the points in a given region appear to move together, there are a sufficient number of apparently opposed motions to weaken seriously the value of the evidence. Unfortunately, an $H\delta$ plate taken on the morning of April 30 is not sharp enough to assist in the identifications. Further discussion of these plates is therefore postponed until additional data become available. On account of the complex character of such storms, a large number of photographs, taken at sufficiently short intervals to permit the flocculi to be identified with certainty, will be required to give satisfactory results. As our recent plates show that these storms are of common occurrence, and probably accompany every group containing several spots, there should be no difficulty in obtaining suitable photographs.

In the present paper I wish to illustrate the phenomena photographed with the aid of *Hα* in the neighborhood of a spot which reached the east limb of the sun at $8^h 16^m$ A. M. on May 26, 1908. A photograph of this spot, made by myself with *Hα* on May 29, at $4^h 26^m$ P. M. Pacific Standard Time, is reproduced in Fig. 1, Plate X. The whirl structure, which is clearly shown by this photograph, is also very distinct, though of somewhat different form, on the photograph of May 28. It is interesting to inquire as to the probable level of the region in which this whirl occurred, and the height of the long dark flocculus south of the spot. For this purpose we may examine photographs of the chromosphere and prominences at the limb, taken on May 25, 26, and 27. In the first of these, made on May 25 at $9^h 18^m$ A. M. (No. 4142), a long narrow prominence, extending toward the north, rises from the limb at position angle 92°, a point about one degree north of the spot. It makes an angle of about 12° with the limb, and fades out at the upper end, its length being approximately 90″ (geocentric). There are other small filamentary prominences in the region extending about 7° north of the spot, and smaller elevations in the chromosphere to the south. At P. A. 98° a bright prominence rises to a height of about 20″ and then slopes to the chromospheric level at P. A. 107°. Near its southern end is an independent filamentary prominence about 55″ high. On May 26, at $6^h 38^m$ A. M. (No. 4144), the prominences shown in Fig. 1, Plate IV, were photographed at the east limb. The lowest point in the chromosphere on this photograph corresponds to the position (P. A. 93°) where the spot crossed the limb about two hours later. It will be seen that these prominences, which extend from P. A. 82° to 106°, cover much of the region in which the whirl structure of Plate X appears. The prominence south of the spot is very bright and its highest point reaches an elevation of about 35″. On May 27, at $5^h 22^m$ P. M. (No. 4152), a prominence about 25″ high extends from position angle 105° to 109°. This is doubtless the eastern extremity of the strong flocculus in Plate X, which may be there seen curving toward the spot.

We may now pass in rapid survey the more important photographs of the disk. On May 28, at $6^h 58^m$ A. M. (No. 4157), the spot is near the east limb and the whirls are well shown. To the east of the spot is a long narrow line of bright hydrogen. On May 29, at

PLATE X

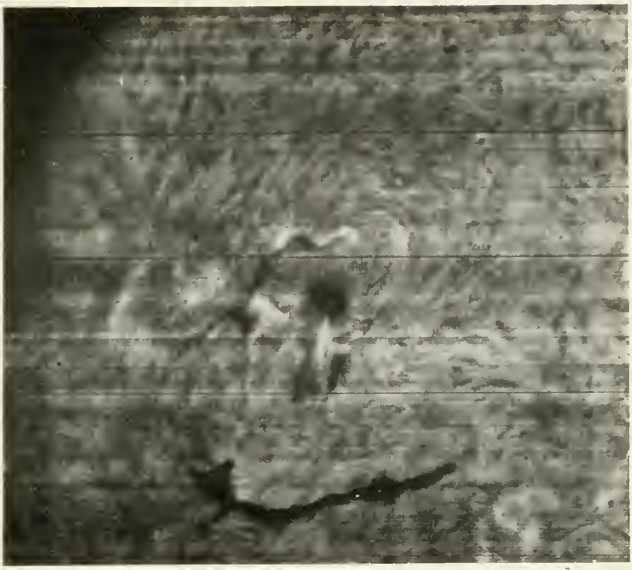


FIG. 1.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, May 29, 4^h 26^m P. M. Scale: Sun's Diameter = 0.3 Meter

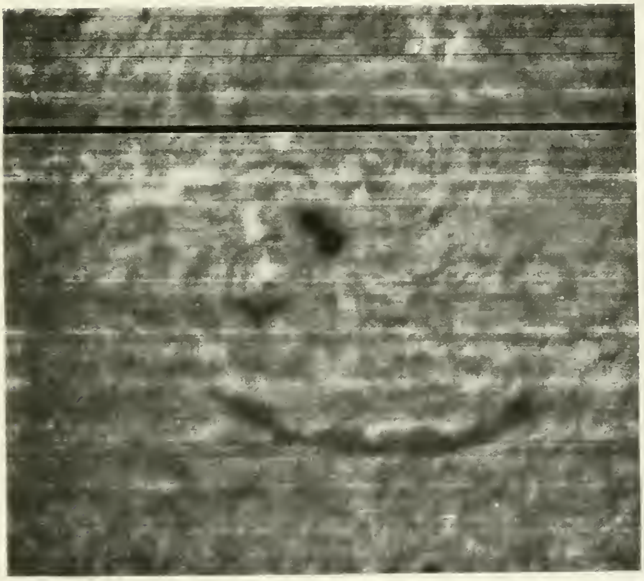


FIG. 2.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, June 2, 6^h 10^m A. M. Scale: Sun's Diameter = 0.3 Meter

$6^h\ 24^m$ A. M. (No. 4171), the whirls are very distinct and differ in many respects from those shown on May 28. Eruptive regions of bright hydrogen are seen southeast and west of the spot. The eastern end of the long dark flocculus is changing in form, and bridges are appearing over the spot. Negative No. 4175, taken $1^h\ 19^m$ later, seems to show distinct changes in the whirls, though they are not measurable. On May 29, at $4^h\ 26^m$ P. M. (No. 4176), the whirls resemble those shown in negative No. 4175, but exhibit some marked changes. An eruption which appears on the former plate southeast of the spot continues, but is changed in form and less brilliant than before. A strong eruption, of peculiar form, appears southwest of the spot, and bright hydrogen to the northeast. Strong dark flocculi have also developed at many points around the spot. The eastern end of the long dark flocculus is still changing, and a projection appears west of its center (see Plate X). A negative taken on the same day at $5^h\ 13^m$ P. M. (No. 4178) shows further changes in both bright and dark structure, especially in the region southwest of the spot. A fork has developed in the western end of the long dark flocculus, and a small but very dark flocculus appears just west of the spot. Another photograph (No. 4179), the first exposure of which was made at $5^h\ 26^m$ P. M., shows a bright eruption west of the spot, where the small dark flocculus appears on No. 4178. The eruption underwent considerable change of form while the five exposures on this plate, separated by intervals of a few minutes, were being made. At $6^h\ 04^m$ P. M. negative No. 4181 shows that the eruption had subsided and brings out other definite changes in structure near the spot. The small dark flocculus has disappeared. On May 31, at $8^h\ 09^m$ A. M. (No. 4188), the fork at the western extremity of the long dark flocculus has partially closed. No eruptions appear west of the spot, but there are bright ones to the southeast. Other important changes are evident, and the two bridges across the spot are conspicuous. On June 1, at $6^h\ 30^m$ A. M. (No. 4189), the fork at the western end of the long dark flocculus appears more nearly as it did in negative No. 4181, and the two bridges over the spot are very marked. A negative taken 15 minutes later (No. 4190) shows distinct changes, especially in the region south and southeast of the spot. At $5^h\ 08^m$ P. M. of the same day negative No. 4193 shows a more distinct whirl near the spot, and the long dark flocculus appears to be growing shorter at its eastern end. On June 2, at $6^h\ 10^m$ A. M. (No. 4196), the whirling structure is very marked and more nearly symmetrical about the spot, which is divided into two parts (Fig. 2, Plate X). At $7^h\ 27^m$ A. M. (No. 4198) the whirl is also very marked and somewhat changed in form.

Up to this time the changes, while in many cases rapid, were not especially violent. On June 3, in an interval of about ten minutes, a remarkable transformation occurred. The long dark flocculus, which had been gradually changing in form and position, was suddenly drawn into the spot. As Fig. 2, Plate X, illustrates, the whirls were very conspicuous on the preceding day. A series of photographs, nine of which were made on negative No. 4201, between $4^h\ 48^m\ 09^s$ P. M. and $5^h\ 13^m\ 54^s$ P. M., and one, showing the entire disk, on negative No. 4202, at $5^h\ 22^m$ P. M., records the changes which took place during this time. These photographs were taken by Dr. C. E. St. John, who joined the Observatory staff in May, and is sharing with me the observational work with the five-foot spectroheliograph during Mr. Ellerman's absence on vacation. Three of these have been selected for reproduction. Fig. 1, Plate XI, is enlarged from a photograph made at $4^h\ 58^m\ 16^s$ P. M. (time of transit of spot across collimator slit of spectroheliograph). At $5^h\ 01^m\ 21^s$ the large dark flocculus is apparently unchanged in form. At $5^h\ 04^m\ 21^s$ an exposure, which is not quite so well defined, gives no certain evidence of change. The next exposure, made at $5^h\ 07^m\ 06^s$, clearly shows the development of a fork at the eastern end of the flocculus, with traces of a very faint curved extension toward the larger spot. The position of the end of the fork (*C*), as measured on this photograph, is given below, but the extension is too faint to be measured with certainty. The next exposure, made at $5^h\ 10^m\ 52^s$, shows the fork and part of the extension, but the definition is poor and the position of the end of the extension uncertain. The last exposure on this plate, made at $5^h\ 13^m\ 54^s$, is reproduced in Fig. 2, Plate XI. This admits of fairly satisfactory measurement, the results of which are given below. The spot region on negative No. 4202, made at $5^h\ 22^m$ P. M. (time of transit of spot), is reproduced in Fig. 1, Plate XII. Here the definition and contrast are

PLATE XI

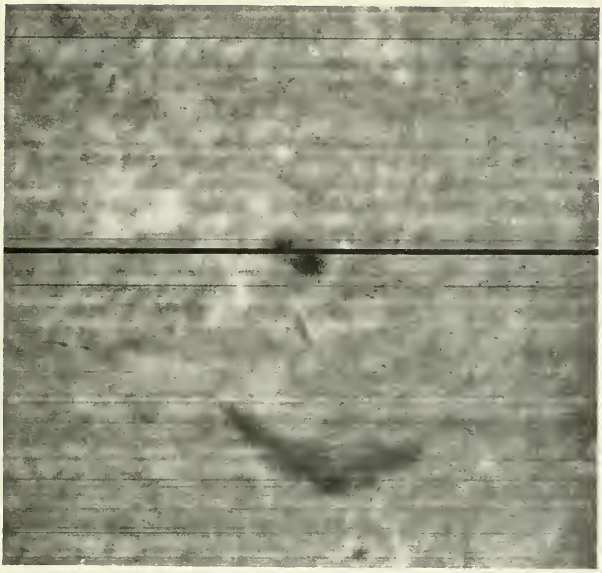


FIG. 1.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, June 3, 4^h 58^m 16^s P. M. Scale: Sun's Diameter = 0.3 Meter

FIG. 2.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, June 3, 5^h 13^m 54^s P. M. Scale: Sun's Diameter = 0.3 Meter

PLATE XII

FIG. 1.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, June 3, 5^h 22^m P. M. Scale: Sun's Diameter = 0.3 Meter

FIG. 2.—SUN-SPOT AND HYDROGEN ($H\alpha$) FLOCCULI
1908, June 4, 6^h 12^m A. M. Scale: Sun's Diameter = 0.3 Meter

also poor, but the extension, reaching nearly to the spots, is sufficiently well shown, as well as a dark flocculus which developed southeast of the smaller spot.

With the aid of the monocular attachment of the stereocomparator I have made a careful examination of all the photographs, and Miss Ware has measured the positions of the long dark flocculus with the heliomicrometer. If we call *A* the western extremity of this flocculus, *B* its eastern extremity, and *C* its point of nearest approach to the spot, we have the results of the measurements in Table I, which also include the positions of the two spots.

If we now take the measured differences in longitude and latitude of the large spot and the points *A*, *B*, and *C* respectively, and compute the corresponding distances, we have the results given in Table II.

These results show that the long dark flocculus gradually shortened, its eastern extremity apparently moving inward along the flocculus, while the distance of its western extremity from the spot did not change in a systematic manner. Accuracy of measurement is out of the question, as the flocculus varied so much in form from day to day that there can be no certainty in the identification of points that appear to correspond. A comparison of the series of photographs taken during the period of rapid development shows that the form and position of the main body of the flocculus did not greatly alter in this short interval, though the maximum of intensity moved rapidly toward the spots, leaving the body of the flocculus very faint. Even on these photographs, however, the velocity of the motion toward the spot cannot be precisely measured, partly because of the difficulty of determining where the extension ends and also because the time of the beginning of the phenomenon doubtless did not exactly coincide with the moment of exposure 6. Between exposures 6 and 7 we find for the point *C* a change of 1°9 in latitude and 1°5 in longitude. This corresponds to a motion of 2°4 in 195 seconds, or 177 km per second. Between exposures 7 and 9, in an interval of 408 seconds, there was a change of 3°0 in latitude and 0°4 in longitude, giving a velocity of 89 km per second. Eight minutes later[1] the extension had divided and moved nearly to the spots, the resultant

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[1] The time of negative No. 4202 is recorded only to the nearest minute.

motion for each extremity being 2°8, giving a velocity of 71 km per second.

TABLE I

Negative No.	Date	Point	Longitude	Latitude	Remarks
4176..........	May 29, 1908	A	32°0 E	5°8 S	B and B′ are the two extremities of eastern end of flocculus
	4^{h} 26^{m} P. M.	B	48.6	13.6	
		B′	46.7	12.8	
		Spot	45.8	3.0	
		Spot	44.4	3.1	
4189..........	June 1, 1908	A	3.9 W	5.5 S	
	6^{h} 30^{m} A. M.	B	13.0 E	13.1	
		Spot	10.2	2.3	
		Spot	8.6	2.6	
4193..........	June 1, 1908	A	9.7 W	4.0 S	
	5^{h} 08^{m} P. M.	B	6.4 E	12.9	
		Spot	3.5	3.0	
		Spot	not measu	reable	
4196..........	June 2, 1908	A	16.9 W	5.5 S	A and A′ are the two extremities of western end of flocculus
	6^{h} 10^{m} A. M.	A′	16.2	4.5	
		B	2.9	12.4	
		Spot	2.8	2.8	
		Spot	4.1	3.1	
4201, Exp. 5...	June 3, 1908	A	38.3 W	5.8 S	
	5^{h} 01^{m} 21^{s} P. M.	B	23.9	11.1	
		Spot	22.5	2.6	
		Spot	24.2	2.7	
4201, Exp. 6...	5^{h} 04^{m} 21^{s} P. M.	A	35.8 W	8.2 S	
		B	23.6	11.2	
		C	25.5	11.1	
		Spot	22.5	2.6	
		Spot	24.4	2.8	
4201, Exp. 7...	June 3, 1908	A	35.9 W	8.1 S	
	5^{h} 07^{m} 06^{s} P. M.	B	23.5	11.0	
		C	24.0	9.2	
		Spot	22.5	2.5	
		Spot	24.4	2.7	
4201, Exp. 9...	5^{h} 13^{m} 54^{s} P. M.	A	35.5 W	8.0 S	
		B	23.6	11.0	
		C	23.6	6.2	
		Spot	22.6	2.6	
		Spot	24.4	2.7	
4202..........	5^{h} 22^{m} P. M.	C	23.0 W	3.5 S	C approaches eastern spot
		C′	23.8	3.4	C′ approaches western spot
		Spot	24.5	2.6	
		Spot	22.7	2.5	

TABLE II

No. and Date	Longitude			Latitude			Distance		
	A-Spot	B-Spot	C-Spot	A-Spot	B-Spot	C-Spot	A-Spot	B-Spot	C-Spot
4176, May 29, $4^{h}\ 26^{m}$ P. M. . .	+12°.4	−4°.2		+2°.7	+10°.5		12°.7	11°.3	
4189, June 1, $6^{h}\ 30^{m}$ A. M. . . .	+12.5	−4.4		+2.9	+10.5		12.8	11.4	
4193, June 1, $5^{h}\ 08^{m}$ P. M. . . .	+13.2	−2.9		+1.0	+ 9.9		13.2	10.3	
4196, June 2, $6^{h}\ 10^{m}$ A. M. . . .	+12.8	−1.2		+2.4	+ 9.3		13.0	9.4	
	+12.1			+1.4			12.1		
4201, June 3									
Exp. 5, $5^{h}\ 01^{m}\ 21^{s}$ P. M. . . .	+14.1	−0.3		+3.1	+ 8.4		14.4	8.4	
Exp. 6, $5^{h}\ 04^{m}\ 21^{s}$ P. M. . . .	+11.4	−0.8	+1.1	+5.4	+ 8.4	+8.3	12.6	8.4	8.4
Exp. 7, $5^{h}\ 07^{m}\ 06^{s}$ P. M. . . .	+11.5	−0.9	−0.4	+5.4	+ 8.3	+6.5	12.7	8.3	6.5
Exp. 9, $5^{h}\ 13^{m}\ 54^{s}$ P. M. . . .	+11.1	−0.8	−0.8	+5.3	+ 8.3	+3.5	12.3	8.3	3.6
4202, June 3, $5^{h}\ 22^{m}$ P. M. . . .			C–E. Spot =0.3 C′–W. Spot =0.7			C–E. Spot =0.8 C′–W. Spot =1.0			C–E. Spot =1.0 C′–W. Spot =1.1

In order to check these measures, the stereocomparator was used to mark all of the points on a single plate, which was then measured differentially. The resulting velocities came out 140, 86, and 76 km per second respectively. Since the errors due to imperfect superposition in the stereocomparator should not differ markedly from those arising from a similar source in the heliomicrometer, the second set is given the same weight as the first. The differences among the three velocities cannot be trusted, though the evidence favors the view that the first velocity was actually higher than the others. The mean of the six measures (106 km) will at least serve to give the order of the maximum velocity in the vortex.

The appearance of the spot and surrounding region 13 hours after the rapid changes described above is shown in Fig. 2, Plate XII. The straight radial lines in this photograph are in marked contrast to the curved structure previously shown. The eastern of the more plainly marked radial lines is found by measurement to be a short distance to the east of the extension from the large flocculus to the spots shown in Fig. 2, Plate XI. The forked connection to the two spots has disappeared and a strong dark flocculus has developed at the southern extremity of the radial line, mainly on its eastern side. With the stereocomparator the main body of the large flocculus is found to resemble its former appearance in some particulars, but the distribution of intensities is very different and many changes in outline have occurred. In the photograph of June 5, $7^h 05^m$ A. M. (No. 4220), the radial structure surrounding the spots is greatly altered and the flocculus, no longer recognizable, has developed a large extension toward the west (Fig. 1, Plate XIII[1]). A notable feature of this photograph is the amount of bright eruptive hydrogen in the region surrounding the two spots. Some eruptive matter also appears in the photographs of the preceding day, but here it is greatly augmented. A photograph taken on the same day, at $5^h 19^m$ P. M. (No. 4227), is reproduced in Fig. 2, Plate XIII. It will be seen that the eruptions continue, and that the dark flocculi have undergone further important changes. The most notable of these is the connection which appears to be re-established between the two spots and the dark flocculus south of them. Apparently the dark hydrogen is

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[1] There is a defect in this plate near the spots.

PLATE XIII

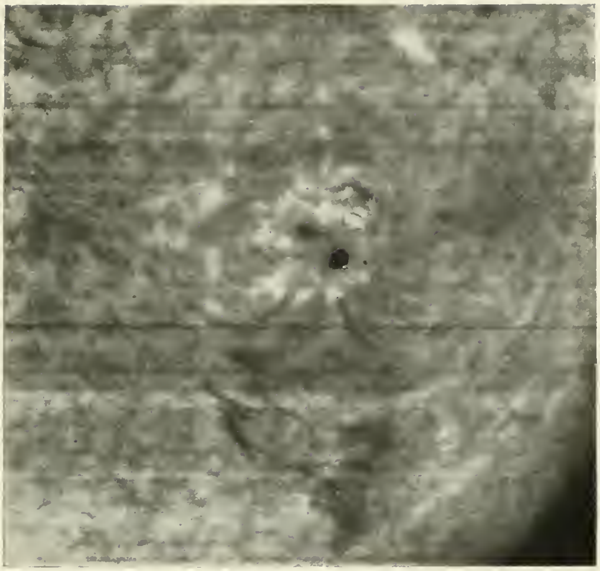

Fig. 1.—Sun-Spot and Hydrogen ($H\alpha$) Flocculi
1908, June 5, $7^{h}\ 05^{m}$ a. m. Scale: Sun's Diameter = 0.3 Meter

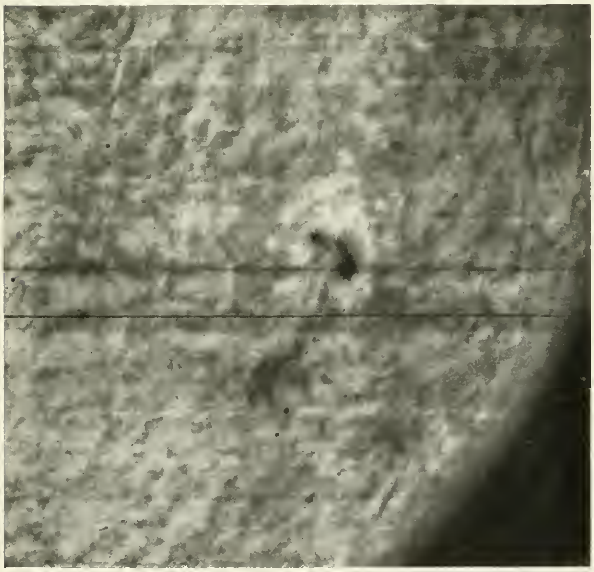

Fig. 2.—Sun-Spot and Hydrogen ($H\alpha$) Flocculi
1908, June 5, $5^{h}\ 19^{m}$ p. m. Scale: Sun's Diameter = 0.3 Meter

again being drawn into the spots. On June 7, at $7^h 56^m$ A. M. (No. 4244), a faint prominence appears on the limb south of the position of the spot. On June 8, at $7^h 42^m$ A. M., negative No. 4252 shows a group of prominences closely resembling in form those reproduced in Fig. 1, Plate IV, but very much less brilliant. On June 9 no prominence was photographed in this region.

As already remarked, the distance from the spot of the western extremity of the large flocculus did not vary systematically. The eastern extremity, on the contrary, commenced on June 1 to approach the spot, and continued to do so until the sudden change occurred on June 3. Up to this time the velocity, instead of showing signs of acceleration, was apparently retarded, but the changing form of the flocculus leaves this point uncertain. On the photograph of May 29 (No. 4176) the whirl is most conspicuous north of the spot, where its extreme distance is about equal to that of the western end of the large flocculus. Apparently, however, the flocculus did not fall completely under the influence of the vortex until June 1, when its eastern extremity was $11^\circ\!.4 = 140{,}000$ km from the spot. The fact that the minimum distance of the western end always exceeded this quantity may account for its escape.

In view of the nature of the phenomena described in this paper, and the fact that evidences of whirls or radial structure have been shown, in connection with several different spots, on a large number of $H\alpha$ photographs, one is greatly tempted to enter at once into a discussion of the sun-spot theories of Faye, Reye, Emden, Halm, Bigelow, and Eckholm, all of which assume the existence of cyclones or vortices within the photosphere or the solar atmosphere. It is the part of prudence, however, to defer such discussion until our daily increasing supply of photographs is considerably enlarged. Moreover, I have devised improved methods for comparing photographs, which should facilitate the identification of objects for measurement, and experiments are also in progress with the purpose of bringing more clearly before the eye the nature of the changes which take place within the vortices. A simple kinetoscope has been advantageously used to observe the rapidly changing phenomena of June 3, and more elaborate apparatus of this kind will soon be available.

It may be well to direct attention, however, to certain points which have been noted:

1. In the series of photographs (on negatives Nos. 4201 and 4202) which show the large flocculus in the act of being drawn into the spots, the small flocculi near the spots remain almost unchanged in position, perhaps because of difference of level.

2. Except in the case of the large flocculus, attempts to detect evidences of motion toward the spots have not yet proved successful, even along apparent lines of flow.

3. Negative No. 4196, taken on June 2, shows a dark comet-like object (apparently defining a line of flow) intersecting a bright eruptive flocculus. The appearance suggests that the eruption does not rise to the level of the vortex.

4. Photographs of the $H\alpha$ line across bright flocculi, made in the second- and third-order spectra of the 30-foot tower spectrograph, indicate that this line has a complex structure which will require careful investigation.

5. Since the velocity of the hydrogen drawn into the vortex is of the same order as that of eruptive prominences, distortions of the hydrogen lines at the limb may be due to the motion of this gas in vortices. If the line of sight were to pass through a vortex, distortions toward violet and red observed at the same point might result from motions of approach and recession on opposite sides of the vortex.

6. The appearance of numerous hydrogen eruptions after the event of June 3 suggests that the hydrogen drawn down by the vortex subsequently rose to the surface in the neighborhood of the spots.

7. In view of the fact that the distribution of the hydrogen flocculi frequently resembles that of iron filings in a magnetic field, it is interesting to recall the exact correspondence between the analytical relations developed in the theory of vortices and in the theory of electro-magnetism.[1]

8. The gradual separation of the spots should not be overlooked.

Without entering at present into further details, a single suggestion relating to the possible existence of magnetic fields on the sun may perhaps be offered. We know from the investigations of

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[1] See Lamb, *Hydrodynamics*, third edition, p. 201.

Rowland that the rapid revolution of electrically charged bodies will produce a magnetic field, in which the lines of force are at right angles to the plane of revolution. Corpuscles emitted by the photosphere may perhaps be drawn into the vortices,[1] or a preponderance of positive or negative ions may result from some other cause. When observed along the lines of force, many of the lines in the spot spectrum should be double, if they are produced in a strong magnetic field. Double lines, which look like reversals, have recently been photographed in spot spectra with the 30-foot spectrograph of the tower telescope,[2] confirming the visual observations of Young and Mitchell. It should be determined whether the components of these double lines are circularly polarized in opposite directions, or, if not, whether other less obvious indications of a magnetic field are present. I shall attempt the necessary observations as soon as a suitable spot appears on the sun.

Mount Wilson Solar Observatory
June 20, 1908

REMARKS ON THE PLATES

As it seems to be impossible to obtain illustrations which accurately represent the original negatives, certain remarks regarding the plates are required.

Plate III.—Both figures are fairly satisfactory except that the limb of the sun, in the lower right-hand corner, is not properly shown.

Plate IV, Fig. 1.—The position angles of various points in the prominences are given in the text of the article. The faint parallel lines, which make an acute angle with the sun's limb, are due to a slight irregularity in the motion of the spectroheliograph.

Plate IV, Fig. 2.—The black dots are defects produced in the sensitizing process.

Plate IV, Fig. 3.—The parallel lines are due to the cause mentioned above.

Plate V.—This plate will serve to give a general idea of the appearance of the $H\alpha$ photograph of April 30, but fails to show the flocculi in their proper intensity. Although many bright flocculi appear to be present, especially in the upper part of the image, the original negative actually shows very few of these objects, the most conspicuous ones being in the midst of the great storm area in the southern hemisphere. For details see Plates VI and VII The parallel vertical bands are due to a periodic motion of the spectroheliograph.

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[1] J. J. Thomson, *Conduction of Electricity through Gases*, p. 164.

[2] Hale, *Contributions from the Mount Wilson Solar Observatory*, No. 23; *Astrophysical Journal*, **27**, 204, 1908.

Plate VI.—As it was found by experiment that the flocculi on the photograph of April 30 are most accurately represented on a negative print, Plates VI and VII are reproduced in this way. Thus the light objects on both of these plates represent the dark *H*α flocculi. The dark structure in the midst of the storm area in Plate VI is luminous hydrogen. The quality of this plate is more satisfactory than that of any other in the present collection.

Plate VII.—This gives a fair idea of the flocculi in this region, though the limb is not well reproduced and certain regions near the spots and in the lower part of the plate are too black.

Plate VIII.—The scale is so small that this illustration serves merely to indicate the distribution of the sun-spots on April 30, and the apparently insignificant nature of the group lying within the great storm area (near the center). The orientation is the same as for Plate V.

Plate IX.—This gives a fair idea of the appearance of the calcium (H_2) flocculi, though the limb is not well reproduced. The orientation is the same as for Plate V.

Plate X, Fig. 1.—The only bright flocculi that should appear in this figure are those in the neighborhood of the spot.

Plate X, Fig. 2.—The background comes out too bright, giving the appearance of bright flocculi in regions where they are not present. The only objects of this class shown by the original negative are very conspicuous in the figure.

Plate XI, Fig. 1.—This gives a fair idea of the original negative, the contrast of which is not very strong.

Plate XI, Fig. 2.—The contrast of the original is much stronger than in the case of Fig. 1, hence the bright flocculi near the spot are relatively too conspicuous. The background in the upper part of the figure is also too bright.

Plate XII, Fig. 1.—The original is lacking in contrast. The region to the left of the spot should be much darker than it appears in the cut.

Plate XII, Fig. 2.—This is a fairly satisfactory reproduction, though the bright flocculi should be somewhat stronger.

Plate XIII, Fig. 1.—Except for a defect in the photograph, the bright flocculi surrounding the spot are fairly well shown. In other parts of the figure, however, the background comes out too bright.

Plate XIII, Fig. 2.—This is a fairly satisfactory reproduction, though the background is too bright in various places.

PRELIMINARY NOTE ON THE ROTATION OF THE SUN AS DETERMINED FROM THE MOTION OF DARK CALCIUM FLOCCULI

By PHILIP FOX

In the measurement with the globe machine of heliographic positions of the calcium flocculi shown on the Rumford spectroheliograms I have also included measurements of dark calcium flocculi wherever they were prominent features on the negatives. These dark flocculi are more easily recognizable when they are long and narrow. For such a flocculus it is my custom to measure the longitude east or west from the central meridian for each degree of latitude for all the parallels which the flocculus crosses.

Mr. C. Michie Smith has cited evidence that the dark calcium flocculi are prominences seen in projection on the disk. Observations by Evershed, by Buss, and by Hale and Ellerman are in accord. I have accumulated ample evidence from the Rumford spectroheliograms to confirm this. Plates obtained on November 7, 1907, give a good example of the coincidence in position angle of a dark flocculus at the limb and a prominence at 151°. Only a small percentage of the prominences shown at the limb, when carried upon the disk by the rotation, can be clearly followed there as dark calcium flocculi: I cannot say, as yet, what particular kind of prominence will be projected strongly dark on the disk.

Further indication that the dark calcium flocculi are high-level phenomena is shown by their coincidence with the dark hydrogen flocculi, pointed out by Hale and Ellerman.[1] Concerning this coincidence I may say that in general the dark hydrogen flocculi are more obvious than those of calcium, and I use the hydrogen plates when available, to facilitate the detection of the dark calcium flocculi. Stimulated by the success of Hale and Ellerman in obtaining negatives using the $H\alpha$ line, I have begun such a series of plates which should be particularly serviceable in this regard. The dark hydrogen flocculi are very plain, and careful examination of the calcium

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[1] *Publications of the Yerkes Observatory*, Vol. III, Part I, Plate VIII.

plates shows the coinciding flocculi to be present. The number of instances where prominences are traceable on the disk should in this way be greatly multiplied. A plate obtained today, June 15, 1908, gives a good instance at 107°. What success I have had with the $H\alpha$ exposures I owe to Mr. Wallace, who prepared the "pan-iso" plates for the work.

TABLE I

Flocculus Number, Plate Number, and Date	Helio-graphic Latitude	Diurnal Motion, Sidereal	Diurnal Motion, Synodic	Longitude from Central Meridian		
				First Day	Second Day	Third Day
Flocculus No. 1 Σ_s 1122, 1904, July 27, $8^h\ 15^m$ Σ_s 1130, 1904, July 28, $8^h\ 18^m$	−23	14°.42	13°.47	−25.0	−11.5	
	−24	14.02	13.07	−26.1	−12.3	
	−25	13.62	12.67	−26.4	−13.7	
	−26	14.12	13.17	−27.4	−14.2	
	−27	13.02	13.07	−27.9	−14.8	
	−28	13.92	12.97	−28.1	−15.1	
	−29	13.52	12.57	−28.2	−15.6	
	−30	13.72	12.77	−28.5	−15.7	
	−31	13.92	12.97	−28.5	−15.5	
Flocculus No. 2 Σ_s 1207, 1904, Aug. 23, $8^h\ 59^m$ Σ_s 1218, 1904, Aug. 24, $8^h\ 16^m$ Σ_s 1234, 1904, Aug. 25, $8^h\ 41^m$	−24	14.14	13.18	−32.5		− 6.3
	−25	14.04	13.08	−33.0	−20.5	− 7.0
	−26	14.14	13.18	−33.9	−20.9	− 7.7
	−27	14.32	13.36	−34.8	−21.6	− 8.1
	−28	14.34	13.38	−35.4	−22.3	− 8.8
	−29	14.55	13.59	−36.1	−23.0	− 9.1
	−30	14.44	13.48	−37.0	−24.0	−10.2
	−31	14.19	13.23	−37.2	−24.5	−10.9
	−32	14.04	13.08	−37.4	−25.0	−11.4
	−33	14.62	13.66		−26.0	−12.1
	−34	14.03	13.07		−26.5	−13.2
	−35	13.93	12.97		−27.3	−14.1
Flocculus No. 3 Σ_s 1516, 1905, Feb. 17, $10^h\ 51^m$ Σ_s 1519, 1905, Feb. 18, $10^h\ 54^m$	+21	14.08	13.07	−11.5	1.6	
	22	13.98	12.97	−11.7	1.3	
	23	14.28	13.27	−11.8	1.5	
	24	14.28	13.27	−12.2	1.1	
	25	14.38	13.37	−12.7	0.7	
	26	13.88	12.87	−13.1	− 0.2	
	27	14.68	13.67	−14.8	− 1.1	
	28	13.88	12.87	−15.2	− 2.3	
	29	14.08	13.07	−16.2	− 3.1	
	30	14.18	13.17	−17.2	− 4.0	
	31	14.08	13.07	−18.3	− 5.2	
Flocculus No. 4 Σ_s 1543, 1905, Mar. 8, $11^h\ 19^m$ Σ_s 1546, 1905, Mar. 9, $11^h\ 05^m$	20	14.43	13.43	− 6.1	7.2	
	21	14.63	13.63	− 7.0	6.5	
	22	14.73	13.73	− 7.9	5.7	
	23	14.43	13.43	− 8.9	4.4	
	24	14.73	13.73	− 9.8	3.8	

The evidence shows that the dark calcium flocculi are of the same order of height in the solar atmosphere as the hydrogen features and would therefore probably give results for the rotation of the sun in harmony with the hydrogen determinations. Two recent determinations of the solar rotation, the first by Hale,[1] giving values derived from the motions of hydrogen flocculi, the second by Adams,[2] from displacements of the hydrogen lines, show constant period for all latitudes, though the two methods yield a difference of nearly a degree in the diurnal motion.

I have collected in Table I my measurements of four dark flocculi. It should be pointed out that measurements of these high-level features should be confined to regions not too remote from the central meridian, for in projection they are displaced from the center of the disk and the resulting angular velocities would be too large. If the prominences were of considerable height this error would be very serious. I have discarded the observations of two dark flocculi because their longitude was greater than 40° from the central meridian. Two others were discarded because they extended nearly east and west, and the longitude for a given parallel was too uncertain.

I have collected the diurnal motions in Table II.

TABLE II

Helio-graphic Latitude	North			South			Mean Diurnal Motion	Group Mean
	3	4	Mean	1	2	Mean		
20°		14°.43	14°.43				14°.43	14°.32
21	14°.08	14.63	14.35				14.35	
22	13.98	14.73	14.36				14.35	
23	14.28	14.43	14.35	14°.42		14°.42	14.38	
24	14.28	14.73	14.51	14.02	14°.14	14.08	14.29	
25	14.38		14.38	13.62	14.04	13.83	14.10	14°.10
26	13.88		13.88	14.12	14.14	14.13	14.11	
27	14.68		14.68	13.02	14.32	13.67	14.17	
28	13.88		13.88	13.92	14.34	14.13	14.01	
29	14.08		14.08	13.52	14.55	14.03	14.05	
30	14.18		14.18	13.72	14.44	14.08	14.13	
31	14.08		14.08	13.92	14.19	14.06	14.07	14°.14
32					14.04	14.04	14.04	
33					14.62	14.62	14.62	
34					14.03	14.03	14.03	
35					13.93	13.93	13.93	

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[1] *Astrophysical Journal*, **27**, 219, 1908.

[2] *Ibid.*, **27**, 213, 1908.

The material is far too meager and the range of latitudes too small to warrant conclusions concerning polar retardation; but it is safe to say, after a comparison with the summarized results in Hale's paper,[1] that the motion agrees more closely with the motion of the hydrogen flocculi than with the hydrogen of the reversing layer, although the values are even closer to those of H_2 calcium.

YERKES OBSERVATORY
June 15, 1908

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[1] *Loc. cit.*, Table III.

A STUDY OF THE ELECTRIC SPARK IN A MAGNETIC FIELD

By HELEN E. SCHAEFFER

A study of the deflection which magnetic and electrostatic fields produce upon the electric discharge at low pressures has given a clue to the nature of the particles concerned in the discharge, and has made possible measurements of their velocity and of the ratio of their charge to their mass. A similar study of the spark-discharge at atmospheric pressure has not been published, and it is the purpose of the present paper to present the results of such a study. The investigation has been undertaken with the idea that if a proper combination of conditions could be secured, a magnetic field might cause a deflection of such a character and magnitude as to separate the constituent parts of the spark, thus securing, as it were, a differentiation in space. Moreover, since the reflection from a mirror in rapid rotation indicates the time-changes which occur, the image thus obtained of the spark dispersed in a magnetic field would show the twofold separation of time and of space, and it was hoped that this separation might lead to a more detailed acquaintance with the mechanism of the electric spark.

Professor J. J. Thomson in his book, *The Conduction of Electricity through Gases*, makes on p. 522 the following statement:

> The effects produced by a magnetic field upon the spark at atmospheric pressure are very slight, although the halo of luminous gas which surrounds the course of the sparks when a number of sparks follow each other in rapid succession is drawn out into a broad band by the magnetic field.

He also states (on the same page) that Precht has found an effect of the magnetic field upon the spark at atmospheric pressure, if the spark terminals consist of a sharp point and a blunt wire; but Precht[1] has described the character of this deflection only so far as to say that its direction agrees with the electro-dynamic laws. Precht's paper is mainly concerned with a study of the different conditions in which one form of the discharge—spark, brush, or glow—becomes

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[1] *Annalen der Physik*, **66**, 676, 1898.

changed into another, and of the changes in the potential difference of the terminals occurring under these different conditions.

The method of using a rapidly rotating mirror to show the separate oscillations which occur in the spark when a condenser is placed in the discharge circuit, was first employed by Feddersen,[1] who made use of it successfully to measure the period of the oscillatory discharge, and thus confirmed the theoretical work of William Thomson (Lord Kelvin). Following him many others have used it for similar measurements.

The use of a rotating mirror and later of a rotating film to gain an insight into the constitution of the electric spark was first made by Schuster and Hemsalech,[2] later by Schenck.[3] A glance at Plate XIV, Fig. 1, showing the appearance of the oscillatory spark when viewed in a rapidly rotating mirror, will make clear the summary of their combined results. The three general features of this discharge as given by Schenck are:

1. A brilliant white straight line due to the first discharge, which is sometimes followed by one or two similar weaker straight lines at intervals of half the complete period of the condenser.
2. Curved lines of light, which shoot out from the poles toward the center of the spark-gap with a velocity constantly diminishing as they move away from the poles. It will be noticed that, as the light advances from one pole, the light moving away from the opposite pole is either very weak or absent altogether.
3. A rather faint light, generally of a different color from the curved lines of light, which fills up the spark-gap and persists for a certain length of time, especially in the center of the spark-gap, after the oscillations die out.

Schuster and Hemsalech (*loc. cit.*) first found that sufficient self-induction in the discharge circuit causes the air lines to disappear from the spectrum of the spark. Later Hemsalech[4] discovered that when the self-induction is increased, the so-called spark lines disappear, whereas the arc lines in the spectrum of the spark become brighter. Schenck (*loc. cit.*) in turn made this difference the basis of a division of the lines of the spark spectrum into three groups, this division occupying the first part of his paper. These several experimental results as arrived at by Schuster, Hemsalech, and Schenck have all been noted during the present investigation, though their

[1] *Pogg. Ann.*, **116**, 132, 1862.

[2] *Phil. Trans.*, **193**, A, 189, 1900.

[3] *Astrophysical Journal*, **14**, 116, 1901.

[4] *Comptes Rendus*, **129**, 285, 1899.

bearing upon the problem here proposed is less immediate than that of other observations made by them.

The results which have a more intimate bearing here do not relate to the disappearance of the air, spark, and arc lines under certain conditions, but to what is true of them under all conditions. Since the photographs of the spectrum lines taken upon a rapidly rotating film showed the air lines to be entirely absent in all the spectra except that of the initial discharge, Schuster and Hemsalech concluded that only the initial discharge passed through the air.

By a similar method of studying the spectrum lines—the only variation being the use of a rotating mirror instead of a rotating film—Schenck brought out an interesting difference between the spark and arc lines, viz., that the spark lines appear sharply beaded to the end of the line, whereas the arc lines show only indistinct traces of beading, which do not extend to the end of the line. In other words, he concluded that the spark lines are due entirely to oscillations, while the arc lines are due partly to the oscillations and partly to something else which retains its luminosity after the oscillations cease. The spark lines are in the spectrum of the streamers which are described as the second feature of the spark; the arc lines in that of the vapor already mentioned as the third feature.

Furthermore, Schenck (*loc. cit.*) has found that the streamers emanate from the cathode and he has concluded that they do not carry the current. This view is supported by Hemsalech,[1] who, after identifying the streamers with the metallic vapor, advances the theory that the electric charge is not carried by the metallic vapor, but by the nitrogen. As addenda to his paper, Schenck gives the results of his investigation of the effect of a strong magnetic field upon the spark, the investigation having been concerned with the spark in a magnetic field of 10,000 units, both with and without the help of the rotating mirror, though his account as published includes only one feature of the change produced by the magnetic field. I quote from this account:

> With no magnetic field the spark lines and the arc lines extended clear across the gap. With the magnetic field the spark line of magnesium λ 4481 extended outward from each pole only about one-quarter of the way across the gap, leaving

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[1] *Comptes Rendus*, 140, 1103, 1905.

the center free from light of this wave-length, while the arc triplet at λ 5200 extended clear across as it did without the field. When examined with the mirror revolving, the line λ 4481 was broken up into a series of short streamers separated by intervals of darkness, while the arc triplet λ 5200 was in the form of a luminosity which advanced slowly (with a velocity not greater than 0.5×10^4 cm per second) toward the center of the spark-gap being crossed by a series of streamers. The noise of the spark was increased by the magnetic field.

It will be noticed that this description of the image given by the rotating mirror when the spark is in the magnetic field, is not essentially different from that given when the spark is out of the field. Other results relating to the disappearance of the spark lines under certain conditions, though in themselves of minor importance, are necessary to an understanding of conclusions applied by Walter[1] to the results of Schuster and Hemsalech, and involved in the discussion of the present paper. Walter has shown that if the self-induction in the discharge circuit having as spark terminals an alloy of zinc and copper, is increased, the disappearance of the spark lines of zinc before those of copper cannot be explained by the fact that the melting-point of zinc is lower that than of copper, an explanation suggested by Kowalski and Huber[2] in connection with their results. The basis of Walter's objection lies in the fact that under similar conditions he found the spark lines of lead to persist longer than those of copper; whereas, if the difference in the melting-points were the determining factor, the spark lines of lead should, like those of zinc, disappear before the spark lines of copper, since the melting-point of lead is also lower than that of copper. Accordingly Walter,[3] referring to a conclusion reached in one of his earlier investigations, viz., that the metallic vapor in the spark is formed at the negative pole, is led to decide that the metallic vapor must be a result of the disintegration of the cathode. He therefore thinks that the amount of disintegration which occurs at the cathode may be the important factor in determining which lines shall persist longest when the self-induction in the discharge circuit is increased, and he finds that the lines of that metal which suffers most disintegration at the cathode persist longest.

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[1] *Annalen der Physik*, **21**, 223, 1906.

[2] *Comptes Rendus*, **142**, 994, 1906.

[3] *Boltzmann-Festschrift*, 647, 1904.

This conclusion, together with Schenck's observation that the spark lines are affected by the magnetic field, while the arc lines are not, Walter considers a sufficient explanation of the differences which Schenck and Hemsalech have observed in the behavior of the spark lines and arc lines. The metallic particles torn from the cathode by disintegration he thinks carry with them an electric charge which they do not lose until they have reached the center of the spark-gap. The spark lines are characteristic of the light from the metallic particles which carry an electric charge; the arc lines, of that from the metallic particles which have lost their charge.

To explain Hemsalech's result that increase of self-induction causes the spark lines to disappear from the spectrum and the arc lines to become brighter, he says that increase of self-induction lengthens the period of oscillation and decreases the current in the single oscillations. This decrease of current causes a longer interval to elapse between disintegration and luminescence of the particles, thus giving time for a greater number of particles to lose their charge. With added self-induction the ratio of the uncharged particles to those charged increases. Therefore the arc lines characteristic of the uncharged particles are brighter than the spark lines characteristic of the charged particles.

Returning to the results of Schuster and Hemsalech, we find that by means of the curvature which a rotation of the photographic film produces in the metallic spectrum lines, they have obtained as the magnitude of the velocity of the particles of many different metals a value of 4×10^4 cm per second. Schenck, on the other hand, obtaining a value of 25×10^4 cm per second, is led to believe that the difference between his values and those of Schuster and Hemsalech may be due to the fact that they measured the slope of the locus of the extremities of the streamers, while he measured the slope of the streamer itself.

The present investigation may be divided into three parts:

I. A study of the visible space-changes which the presence of a strong magnetic field causes in the spark.

II. A spectroscopic analysis of the different parts into which the spark is spread out under the influence of the magnetic field, this analysis being made solely for purposes of identification.

III. A study of the image of the spark given by a rapidly rotating mirror when the spark is in a magnetic field. The object of this part of the experiment was to get a second differentiation of the spark, viz., a differentiation with respect to time of the space-changes described in Part I.

Three types of electric spark were studied in each of the three parts of this investigation.

1. The spark obtained when neither capacity nor self-induction has been introduced into the secondary circuit of the induction coil.

2. The spark obtained when a capacity of 0.0005 to 0.012 microfarads has been introduced into the secondary circuit.

3. The spark obtained when a capacity of 0.0005 to 0.012 mf and a self-induction of 0.003 henries have been introduced into the secondary circuit.

APPARATUS

The spark was obtained from an induction coil, the primary of which was supplied by a direct current of one to four amperes taken from the 110-volt mains. The potential of the secondary could be raised high enough to produce a 32-cm spark between its poles. With a capacity of 0.012 mf and a self-induction of 0.003 henries in the secondary circuit, a spark of about 2 cm length passed between the metallic terminals. The capacity was obtained from Leyden jars arranged in parallel in the secondary circuit and was varied by gradually changing from a $\frac{1}{4}$-gal. jar to six 1-gal. jars, each 1-gal. jar giving a capacity of about 0.002 microfarads. The self-induction was obtained by placing in the secondary circuit four wire spools arranged in series. An adjustable resistance in the primary circuit served to change the spark from a very noisy to a hissing one. An approximately uniform magnetic field was obtained over a distance of about 2 cm by using truncated cones as the pole-pieces of a large DuBois electro-magnet.

The spectroscopic analysis was made by visual observations and photographs. The former were made by means of a calibrated prism-spectroscope which was mounted upon a carriage that could be moved at right angles to the rays of light falling upon the slit of the spectroscope. In this manner the spectra given by the different parts of the spark could be conveniently studied. The spectrograms were made by means of a Fuess quartz-prism-spectrograph with camera attached.

For the third part of the investigation the image of the spark was reflected from a plane metallic mirror made by Brashear. This mirror was 5 cm in diameter and was mounted so that its rotation was about a horizontal axis. It was driven by a means of an electric motor and could be rotated at a speed of 200 revolutions per second, although a speed of about 50 revolutions per second usually sufficed. The speed of the mirror was measured by the impressions which a bristle attached to its axis made upon a revolving drum. These impressions showed that after the mirror had been in rotation for a short time its speed was practically constant and even such deviations from its constant value as occurred were found to be well within the limit of experimental error.

I. EFFECT OF THE MAGNETIC FIELD

The deflection produced by the magnetic field is most striking when the spark is allowed to pass along the lines of magnetic force or perpendicular to them, the deflection taking the form of circles in the latter case and of spirals in the former. (See Plate XIV, Figs. 3 and 2.) The spirals seem to be wound about cones of revolution, having different angles of divergence, whereas the circles all lie in a plane perpendicular to the lines of magnetic force. In a magnetic field of 1050 units the central threads do not participate in this spiral or circular form.

To appreciate in full detail this effect of the magnetic field upon the spark, a description of the three types of spark-discharge, as they appear both in and out of the field, will be necessary. The first type consists of one or two reddish-white threads which pass directly across the gap and are accompanied by a reddish, luminous vapor that assumes a yellow tinge when the current through the primary circuit is increased. Without the magnetic field this vapor forms an envelope about the central threads: in a parallel field it is deflected into a spiral sheet; in a transverse field into two semicircular sheets which are in the same plane. If the current through the primary circuit is sufficiently small, there is only one such spiral sheet in the first case, and only one plane semicircular sheet in the second. If the current is increased, two spiral sheets or two semicircular ones are present and the latter two are in the same plane, one of them being on either side of the spark-gap. If, however, the spark terminals are drawn sufficiently far apart, one of the two spiral or semicircular sheets disappears entirely. In a field of 12,000 units, however—the strongest that could be obtained with the amount of current available, viz., 19 amperes—no deflection of the central threads could be noticed in either position of the magnetic field.

It was found that a small capacity in the discharge circuit introduced several reddish-white threads into the semicircular and spiral sheets. These threads took the form of spirals in a parallel field, the form of semicircles in a transverse field, and all lay in a single plane perpendicular to the lines of magnetic force. A slightly larger capacity in the discharge circuit made these threads more brilliant and increased their number. Strengthening the magnetic field also increased the number of these threads and their brilliancy. An increase in magnetic field-strength seems therefore to produce the same effect as an increase in capacity.

The second type of spark consisted of a bundle of very brilliant white threads, which were accompanied by little or no vapor. With a capacity greater than 0.002 mf this vapor was not present. In the magnetic field it assumed a circular or spiral form, according to the position of the spark-gap, and was accompanied by thin, brilliant white threads, which likewise were parts of circles or spirals. (Plate XIV, Fig. 5.) This vapor was yellowish in color, whatever terminals were used, and was spread out into a sheet that was so thin as to be almost invisible. The bundle of threads across the gap could not be changed by any available strength of field.

Plate XIV, Fig. 4, shows the central threads and metallic vapor of the third type of spark as they appear without the magnetic field. The threads are not so brilliant as those of the second type of spark, and have the same reddish color for all the metals tried as terminals. The color of this metallic vapor, however, varies with the metal used as spark terminal. With aluminium it is a bright green and shoots out from the electrode instead of enveloping it. With magnesium this vapor is yellow-green; with calcium, pink; with zinc, cadmium, and lead, orange-red with a blue core extending a short distance from the electrode. This vapor does not appear to advance farther from the electrodes as the spark length is increased. It is therefore possible to separate the poles to such an extent that this vapor seems to be entirely absent from the center of the spark. With a given capacity in circuit the length of this vapor increases, however, with an increase of self-induction.

The figure just mentioned was taken from a photographic plate which was not sensitive to the reddish-yellow vapor enveloping the brilliant threads when no magnetic field is present. If the spark terminals are sufficiently far apart or the current through the primary is small this vapor is entirely absent. In the presence of the magnetic field it is changed to bright threads unless the spark terminals are close together. These threads are parts of circles or spirals according to the position of the spark terminals in the magnetic field. Strengthening the magnetic field increases their curvature. The color of these threads varies with the metals used as spark terminals. With aluminium they are reddish-white; with magnesium, red; with calcium, blue; with cadmium, reddish-purple; with zinc, lead, and bismuth, reddish-white. As the capacity and therefore the period is increased, these threads become broader, fewer in number, more red in color—where aluminium is concerned—and tend to depart from the plane perpendicular to the lines of magnetic force in a transverse field. Changing the amount of self-induction in the circuit does not seem to introduce any change into the form or number of the threads; but, if with a capacity of 0.002 mf in a circuit the self-induction is entirely removed, the threads are brilliant white instead of being reddish in color, and they disappear from the immediate region of the central threads, thus decreasing their number considerably. (Compare, Plate XIV, Figs. 7 and 5.) When self-induction is present, these threads which take the form of circles or spirals, according to the position of the spark-gap, can be obtained with a capacity as great as 0.012 mf. Without self-induction it is impossible to obtain any spiral or circular threads with a capacity greater than 0.002 mf. The number of these threads present when the third type of spark is in a magnetic field, passes through a maximum as the capacity is increased from 0.0005 to 0.012 mf, this maximum number occurring when the capacity is about 0.002 mf.

The number of threads present in the second type of spark also passes through a maximum, but here the maximum number occurs when the capacity has a much smaller value, comparable with that obtained from a small parallel-plate condenser. On the other hand, the width of the threads in both types of spark does not pass through a maximum for the range of capacities used, but steadily increases as the capacity is increased. If the electrodes are so far apart that without the magnetic field no vapor envelops the central threads, none of these circular or spiral threads is present when the magnetic field is on. It the electrodes are close together, the vapor is spread by the field into a yellow, circular or spiral sheet, instead of being broken up into brilliant circular or spiral threads.

It requires a much stronger field, however (about 12,000 as compared with 1050), to secure a noticeable change in the central threads. They are twisted by a very strong field·along the spark length into a spiral, much like the thread of a screw, and of small radius. (See Plate XIV, Fig. 6.) A field at right angles to the spark length seems to cause a very slight general curvature in these central threads and also to make them appear crenate, the whole being concave to the spark-gap. The number of spiral turns or small semicircles does not in the latter case remain constant, and this irregularity suggests that these spirals or semicircles may be brought about by a sudden change in the velocity of the particles resulting from a loss or gain of electrons.

With this field of 12,000, the metallic vapor of the third type of spark also undergoes a deflection. In a transverse field it certainly assumes a circular form, but in one that is parallel, its form though much changed is too indistinct to be called that of a spiral.

The results thus obtained when any of the three types of spark is in a magnetic field are interesting if compared with the results obtained by Wehnelt,[1] when a hot lime cathode was used for the discharge at low pressures. He found that the particles emitted by a hot lime cathode bring to luminescence the gas through which they pass, and this luminescence indicates the spiral, or circular paths in which charged particles under the influence of a parallel or transverse magnetic field have been shown theoretically to move.

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[1] *Annalen der Physik*, 14, 425, 1904.

The present investigation seems to show that also at atmospheric pressure there are particles which describe luminous paths in the form of spirals and circles. A much stronger field is necessary to produce the deflection here than at low pressures and the radii of the spirals and circles are much smaller.

These observations seem to justify two conclusions, at least, as regards those particles with which luminescence in the spark at atmospheric pressure is associated:

1. They obey in general the laws of motion which experiment and theory have shown charged particles to obey when at low pressure and under the influence of a magnetic field.

2. The obedience to these laws certainly lends strong support to the view that the particles carry an electric charge.

For two reasons it has at present seemed impracticable to find out whether the curvature of the path of these particles, as given by actual measurement, satisfies an equation deduced from theoretical considerations. The electrical conditions are seriously complicated by the necessity of having the electrodes sufficiently close for the passage of a spark at atmospheric pressure, and it would therefore be difficult to find the true values and directions of the electrical forces. The mathematical theory of the behavior of charged particles in a magnetic field has been worked out only in a general way for atmospheric pressure.

Figs. 7 and 8 show a twofold asymmetry in the deflection produced by a magnetic field: (1) an asymmetry at the electrode itself; (2) an asymmetry in the width of the two semicircular, luminous sheets. The latter asymmetry will be considered first.

Figs. 7, 8, 10, and 11 show the difference in the width of the two semicircular sheets. This difference also seemed to exist in the two spiral sheets, but their position as well as their spiral form made it more difficult to compare their respective widths. When the direction of the current through the primary, or that of the magnetic field is reversed these two sheets exchange places (compare Figs. 11 and 10 with Fig. 8). Furthermore when the current through the primary is decreased, or the distance between the spark terminals is increased, both of the sheets become steadily narrower, until finally a stage is reached where only one of the two is present.

The difference in the width of the two sheets can hardly be explained by the fact that the magnetic field may not have been entirely uniform throughout the region of the spark, since this difference in width was found to persist even in that part of the field which was far from uniform. An explanation might be sought in the fact that on one side of the spark-gap the magnetic field, due to the passage of the current, reinforces the permanent field given by the electro-magnet, while on the other side of the spark-gap, it weakens the permanent field. This explanation, however, would require both sheets to be produced at the same time and this simultaneous passage seems improbable since both sheets are later found to be due to particles of like charge. Fig. 9 seems to indicate that the two sheets are not formed at the same time. This photograph was taken when both sheets appeared to be present; yet it shows only one sheet of threads, thus suggesting that the exposure ($\frac{1}{50}$ sec.) was short enough for the set of threads on one side of the spark-gap to be photographed before that on the other was formed.

At the spark terminals the ends of the sheet are asymmetric in the following respect. One end of the semicircular boundary rests on the point of the electrode, while the other end of the boundary is at some distance from the point of the opposite electrode, as may be seen in Figs. 8, 10, and 11.

It has already been stated that the image given by the rotating mirror shows the particles with which these luminous sheets are connected to be most probably negative. If they are negative, then the direction of the field, together with the direction of the deflection, shows that they *advance* from the point of the electrode and *end* in a straight line extending for some distance along the other electrode.

In terms of the brilliant circular threads, characteristic of the spark which results when both capacity and self-induction are inserted into the secondary circuit, this asymmetric form at the electrode may be described thus: The threads all proceed from the extreme end of the negative electrode and end at different points on the positive electrode, these different points being in a straight line and all lying in the plane of the sheet which is perpendicular to the lines of magnetic force. (See Plate XIV, Fig. 7.)

Actual measurement has shown that these circular threads do not possess the same radius of curvature. The asymmetry at the spark terminal may, accordingly, have no deeper significance than the fact that the circular threads are compelled to end upon different points of the positive terminal because their curvature is different, whereas they all start from the same point of the opposite, negative terminal because its potential is higher than that of any other part.

It has already been noticed, too, that if the conical end of the metal terminal is not perfectly smooth, the sheet sometimes starts from one or two other points in addition to the extreme point of the spark terminal. These few points were very different, however, from the line of points in which the sheet ended on the opposite spark terminal—that line of points lying, together with the axis of the spark terminal, in a plane which was at right angles to the magnetic field. Except at the few points from which the sheet seemed to proceed, a space could be seen between the sheet and the terminal from which the particles appeared to start. At the opposite, positive terminal no such separation could be seen between any part of the sheet and the spark terminal. When, therefore, the sheets seemed to start also from other points of the negative terminal, it was supposed due to the fact that an unevenness of the surface of the terminal caused these points to act as additional centers of discharge.

Fig. 10 shows the change which occurs in the position of the sheets when the direction used above for the magnetic field is reversed. It will be seen that the two sheets interchange sides as though each were turned through an angle of 180° about an axis along the spark length.

Fig. 11 shows another difference in the position of sheets, occurring when the current through the primary is reversed, the sheets here undergoing what might be termed a diagonal inversion. Not only does each sheet turn through an angle of 180° about an axis along the spark length, but each end turns, as it were, through another angle of 180° about an axis perpendicular to the spark length and in the plane of the sheet.

The first type of inversion is in entire agreement with such a change in the deflection, as a moving charged particle would experience in a magnetic field in which the direction has been reversed. The second type is also what the electro-dynamic laws would lead one to expect for reversal of current through the primary of the induction coil.

II. A SPECTROSCOPIC ANALYSIS OF THE DIFFERENT PARTS OF THE SPARK

An image of the semicircular, reddish sheet presented in a transverse magnetic field by the first type of spark was focused upon the slit of a quartz spectroscope. The slit was at right angles to the spark length so that if any differences existed in the various parts of the sheet they might be shown upon the same plate. A magnetic field sufficiently weak to keep out of the sheet all reddish, circular threads was chosen.

Three different spectrograms were made of each of the following metals: aluminium, bismuth, zinc, cadmium, and lead. The first shows the spectrum of the outer part of the semicircular sheet; the second, that of the part containing the bright threads which pass straight across from pole to pole; the third, that of the third type of spark, taken merely as a means of comparison, and for this purpose it answers very well, inasmuch as the presence of self-induction brings into prominence the metallic lines. Plates were taken with the first spectrum directly above the third; others, with the second above the third. The first two spectrograms were given exposures of one hour; the third, of a minute.

As a result of these experiments the luminous sheet was found to present the same spectrum for each metal tried. This was the spectrum of the nitrogen bands and was found to correspond with that obtained from a low-pressure discharge tube containing nitrogen. The spectrum of the bright threads across the gap showed lines, identified visually with the so-called air lines, and lines corresponding in position to the metallic lines which show prominently in the third spectrogram. These three spectra may be seen in Figs. 12 and 13.

Since the sheets here studied show only the nitrogen bands in their spectrum, it seems probable that whereas their form indicates the path of the charged particles through the air, their luminescence is merely that of the air particles and is not in any way shared by a light characteristic of the metallic terminals from which the charged particles appear to come. On the other hand, since the central threads have the metallic lines in their spectrum, there is reason to believe that they are, in some way, associated with particles which emit a radiation characteristic of the metallic terminals; but which cannot be considered as charged until a deflection or some other evidence is obtained.

The presence of the magnetic field introduces into the intensity of the lines a difference which is interesting. It will be remembered that, with the magnetic field absent, a yellowish vapor envelops the central threads, if sufficient current passes through the primary; also that with the field present, this vapor is spread out into a plane sheet passing through the spark-gap and perpendicular to the magnetic field, thus leaving the region about the central threads free from vapor except in the plane of this sheet. If the spark in the magnetic field is viewed side-on, i. e., if the spectroscope is placed so that no luminous vapor intervenes between it and the central threads, the metallic lines are brighter than when the field is absent. On the other hand, if the spectroscope is placed with its slit in the plane of the sheet of luminous vapor, so that the width of this sheet is between it and the central threads, the metallic lines are fainter than when the vapor surrounds the central threads, as always occurs when there is no field. Since an hour's exposure showed no evidence of these metallic lines in the spectrum of the vapor of the first type of spark, it seems probable that the decrease in the intensity of the metallic lines is due merely to the passage of the light through a cloud of particles and not to any such absorption as could cause a reversal.

The difference of intensity just described has also been noticed in the brightest metallic lines shown on the spectrograms of the third type of spark. When this type of spark is viewed side-on, these lines seem at least twice as bright in the field as out of it.

By extending to the second type of spark the spectroscopic analysis made for purposes of identification, it was found that the bundle of brilliant white threads which pass directly across from pole to pole and are undeflected by any available field have the well-known spectrum which presents itself when capacity is introduced into the secondary circuit, a spectrum consisting of bright air lines and fainter metallic lines. The spectrum lines of the circular threads have the same wave-lengths as those of the non-deflectable threads, but they are much fainter. Throughout this paper the word *non-deflectable* is used in a purely relative sense, viz., that the central threads could not be deflected in any available strength of field of 12,000 units. Only for this type of spark is the spectrum of the circular threads the same as that of the threads which pass directly across the spark-gap.

In the third type of spark the investigation was concerned with the spectrum of the bright circular threads, that of the brilliant white central threads, and that of the vapor which extends several mm from the electrodes. All three different spectra were studied for electrodes of aluminium, zinc, bismuth, cadmium, lead, calcium, and magnesium, and no attempt was made to measure the lines with greater accuracy than was necessary for purposes of identification. For the visible spectrum a calibrated prism-spectroscope served to identify the arc, spark, and air lines accurately enough with those given for these metals in the charts of Hagenbach and Konen. The accompanying photographs show the spectrograms of the three different parts of the spark of each metal (taken directly, one above the other, upon the same plate). Plate XIV, Fig. 14, shows the spectrogram obtained when magnesium terminals were used. Fig. 15 shows the spectra of the central threads of each metal, taken one directly above another, and all by focusing upon the slit that part of the spark which is free from the metallic vapor. The time of exposure was two minutes for the spectra of the circular threads and of the central threads; one minute for those of the vapor close to the poles. For the spectra of the central threads the spark-gap was lengthened until the center appeared free from the metallic vapor enveloping the poles. The spectrograms obtained for the seven metals used as spark terminals, together with the visual observations upon the spectra of these metals, gave in general the following results:

1. The circular threads show spectra composed of faint air lines and the bright arc lines characteristic of the metal used. The spark lines appear to be entirely absent.

2. The central threads across the gap show the spectra of the air lines. Plate XIV, Fig. 15, shows that these spectra are practically the same for all the metals used. On some of them the metallic lines

show so faintly that the suggestion is rather that of a diffuse light reflected upon the slit than that of a light coming directly from the threads themselves. This view seems especially valid if one considers that with the spark terminals closer together the metallic lines of this type of spark are very much brighter than the air lines.

3. The vapor near the poles could not be isolated from either the central or the circular threads. Accordingly spectra taken in its region near the spark terminals showed very bright arc and spark lines together with very much fainter air lines. The other two spectra described above in 1 and 2 do not present the spark lines showing these spectra.

Varying the capacity or the self-induction changed only the intensities of the spectrum lines.

III. STUDY OF THE SPARK PLACED IN A MAGNETIC FIELD AND REFLECTED FROM A MIRROR IN RAPID ROTATION

To measure the velocity of the streamers, Schenck, and Schuster and Hemsalech used a method based upon a measurement of the slope of the streamer as given by the mirror in rapid rotation. As the luminescent vapor advanced from the spark terminal toward the center of the spark-gap, the light from this vapor reflected from the mirror when stationary and focused upon the photographic plate described a straight, horizontal line, a true representation of the path of the vapor. When the mirror is in rotation, however, this image is drawn out in a direction perpendicular to that in which the vapor is advancing. The resultant path on the plate is curved because the velocity of the vapor decreases as it approaches the center of the spark-gap.

This method, based upon a measurement of the apparent change of form introduced by the rotation of the mirror, would involve serious complications if it were used to measure the velocity of the particles from which arise the brilliant, circular threads of the spark of the third type. Measurement shows that the curvatures of the threads in a single spark vary considerably among themselves. Accordingly, even if two images of the same single spark-discharge were obtained—the one with the mirror in rapid rotation, the other with it at rest—it would be very difficult to match the threads in the two images and then to measure the change of curvature introduced by the mirror. The existence of such a curvature change, however, suggests a simple method of measuring the velocity of the particles associated with the circular threads, and this method has been adopted in the present investigation. The method is this. The spark is made to pass in a horizontal plane parallel to the horizontal axis of the mirror. The spark terminals are so placed that with the mirror at rest the two ends of each circular thread are at exactly the same distance from the bottom of the photographic plate. When the mirror is set in rapid rotation, the image of each thread shows one end to be farther from the bottom of the plate than the other, this distance being greater for a long thread than for a short one. Evidently a time-interval must have elapsed between the formation of the two ends of the thread, and the existence of this time-interval shows that the luminosity of the circular threads must somehow be produced by the movement of a single set of particles from one pole toward the other, and not by two sets of particles which start simultaneously each from its own pole. From this time-interval may also be calculated the average velocity of particles. This average velocity is equal to the length of the circular path, divided by the time-interval above mentioned. This time-interval bears the same ratio to the time of one revolution of the mirror as that borne to 2π by the angle which is swept through in describing the distance a ($a = y_1 - y_2$, measured along the axis of y, Fig. 16) between the two ends of the thread. By means of a comparator, reading to thousandths of a millimeter, the distance a was measured upon a photographic plate which was moved parallel to the path described by the image of the spark across it. Readings to hundredths of a millimeter were found to be within the limit of experimental error. The length of the circular thread itself was measured by making a fine flexible wire coincide with an enlarged image of the thread, and then measuring the length of this wire after it had been straightened. Two errors are introduced into this latter measurement by the relative motions of the mirror and the particles. These two errors, being of opposite sign, offset each other. When the particle and the mirror are moving in the same direction, the length of the path of the moving particle is shorter in the image than it is in reality, whereas, when they move in opposite directions, the path of the particle is longer in the image than in reality. As both these cases occur in the same semicircular thread the sum of the two errors becomes practically zero. Errors due to a displacement of the image by the rotation of the mirror were found to be well within the limit of experimental error. The spark terminals, besides being placed in such a position, were chosen of such a width and form that they could introduce no serious error into the measurement of a. The accompanying table gives the values of the velocities thus calculated from measurements upon the circular threads.

TABLE I

Number of 1-gallon Leyden Jars in Circuit	Values of the Velocity in cm per sec.
1	6.3×10^4 to 8.5×10^4
2	4.8×10^4 to 6.7×10^4
3	4.4×10^4 to 6.0×10^4
4	4.3×10^4 to 4.9×10^4
5	3.8×10^4 to 7.0×10^4
6	3.9×10^4

It is seen that the velocities are roughly of the order 5×10^4 cm per sec. Within the limit of error it cannot be said that there is any difference for threads of different curvature, nor is there a serious difference when the capacity is gradually changed from that given by one 1-gallon Leyden jar to that given by six 1-gallon Leyden jars.

This method may possibly be used to measure the velocity of the particles associated with the central threads, if the spark length be so adjusted that the threads remain in the same plane throughout their length.

This difference in the position of the two ends of a circular thread, as shown in the image reflected from the rotating mirror, also led to a determination of the sign of the charge carried by the particles whose velocity has just been calculated. According to the direction in which the mirror rotated, the end of the thread last formed was nearer or farther from the horizontal edge of the photographic plate. Thus from the direction of rotation and the position of the ends of the thread on the photographic plate, it was found which end of the thread was first formed, and this fact in turn indicated the pole from which the particle started and the direction in which it was moving. This direction, together with that of the deflection and that of the magnetic field, gave the sign of the charge carried by the particle. It was thus found that a negative charge is carried by the particles to which the easily deflected, circular threads are due.

As already stated, the equations of motion of a charged particle in a magnetic field are still, so far as atmospheric pressure is concerned, very general and incomplete. Moreover, the electrical conditions, complicated by the nearness of the electrodes required for the passage of a spark at atmospheric pressure, introduce other difficulties, so that it is not easy to arrive at an equation which will accurately represent the motion of these charged particles connected with the circular threads. The use of the equation $\frac{1}{\rho}=\frac{eH}{mv}$ in order to find the magnitude of $\frac{e}{m}$ would have no other justification than the fact that the path of these particles has approximately the same circular form as that of the particles in a low pressure discharge under similar magnetic conditions, the curvature of this form in the latter case satisfying the equation just mentioned. Some of the photographs show a change in the curvature of the threads at a distance of about 2 mm from the spark terminals. The radius of curvature then becomes smaller but has a constant value to within 2 mm of the opposite terminal, when it may become greater by as much as 5 per cent. In the present investigation

$$H=1050 \text{ c.g.s. units},$$
$$V=5\times 10^4 \text{ cm per sec.}$$

ρ varied from 0.4 cm to 0.7 cm, as may be seen in the accompanying table which gives the values of ρ for different amounts of capacity in the secondary circuit. If these values are substituted in the equation $\frac{1}{\rho}=\frac{eH}{mv}$, $\frac{e}{m}$ varies from 1.2×10^2 to 0.7×10^2.

TABLE II

Number of 1-gallon Leyden Jars in Circuit	I Series of Measurements Values of ρ in cm	II Series of Measurements Values of ρ in cm
1	0.56	0.42 0.70
2	0.60	0.52 0.54 0.60 0.65
3	0.55	0.50 0.54 0.60
4	0.60 0.55 0.48	0.43 0.45 0.57 0.43
5	0.45	0.45
6	0.40	0.40 0.43

Two or more values of ρ for the same number of Leyden jars are those belonging to different threads upon the same photograph, not several values of ρ belonging to the same thread. $\left\{\begin{matrix}0.57\\0.43\end{matrix}\right.$ are the radii of curvature of different parts of the same thread, 0.57 being the ρ of the parts near the spark terminal.

Measurements were also made upon the slope of the streamers to find how the value obtained for these velocities agreed with the values obtained by Schenck, and Schuster and Hemsalech, Schenck having obtained a value of about 25×10^4 cm per sec.; Schuster and Hemsalech one of 4×10^4 cm per sec.

The measurements made here upon the streamers have shown a decrease in the velocity as the slope was measured from the electrode toward the center of the spark-gap, the values of the velocities ranging from 1×10^5 cm per sec. to 4×10^3 cm per sec. Measurements were taken only upon the part of the streamer which is not in the same direction as the path of the image across the plate.

Moreover, by closely examining the streamers it will be noticed that the second streamer advances farther toward the center of the spark-gap than the first, the third farther than the second, etc., the the brightness of each diminishing as it nears the center of the gap. The slope of each succeeding streamer becomes after a short time less abrupt than that of its predecessor and their points of junction finally lie on one continuous line, which is almost parallel to the path of the image across the photographic plate. It will also be noticed that the space between successive oscillations increases. This increase in space means that the interval of time between the oscillations becomes greater as they die out and this suggests that each streamer, before it joins the next one, approaches the center of the gap more nearly than its predecessors, for the reason that the vapor is there given a longer time to diffuse toward the center. The decrease in slope shows that the change in the velocity of the vapor becomes less abrupt with each successive oscillation, suggesting that the sum total of the forces which act upon the vapor changes less abruptly with each oscillation. This would naturally be expected from the curve of an oscillatory discharge. These observations, together with the results given on p. 141, lead one to think that Schenck may have been mistaken in suggesting —as he did, to explain the difference between his values for the velocity of the streamers and those of Schuster and Hemsalech—that they measured the slope of the *locus* of the extremities of the streamers. Such a locus is almost parallel to the path of the image of the spark across the photographic plate and a measurement of it could not possibly give for the velocity a value comparable with that secured by Schuster and Hemsalech. It seems possible therefore that the velocities measured were actually those of different parts of the streamer; Schenck having measured that of the part very near the electrode; Schuster, that of the part somewhat nearer the center of the spark-gap.

This possibility suggested that there might be for some of the metal terminals a noticeable difference in the parts of the streamer itself. With zinc, cadmium, and bismuth a difference in color was noticed. For a very short distance, not exceeding 2 mm, the streamer was of a brilliant blue color like that of the blue cone noticed in the vapor about the electrode. Then it changed to a dull blue and afterward to an orange-red like that of the vapor at some distance from the electrode. Furthermore the color of the bright blue core is like that of the bright points of light seen where the sheet of vapor of the first type of spark just touches the metal terminals, and where the circular threads touch the terminals in the third type of spark, provided that a capacity less than 0.012 mf is present in the circuit.

Plate XIV, Fig. 17, shows the spectrum of the spark when the spark length is parallel to the slit of the spectroscope. The spark line λ 4481 of magnesium is seen to be present only in the region of the spark terminals, whereas the other lines extend entirely across the spark-gap. When other metals were used as terminals, similar plates, showing the spark lines present only in the neighborhood of the terminals, were obtained.

The photographs show that the vapor represented by the very bright part of the streamer exists for a short time in each oscillation, but does not persist until the next oscillation at that electrode has begun: it therefore does not receive a fresh addition from each successive oscillation. The rest of the vapor, on the other hand, does persist until after the second or still later oscillations have begun, and thus presents a continuous background of light, reinforced by each successive oscillation. Schenck, it will be remembered, found that the image of the spark line given by the rotating mirror was sharply beaded and that the parts of the line are separated by intervals of complete darkness. The arc lines, on the other hand, showed only indistinct traces of beading, such as would be given by a continuous background of light crossed by streamers. These two facts taken in connection with the foregoing description lead to the following inference. The bright core, entering with each oscillation and completely dying out before the next begins, has some association with the spark lines which show by their distinct beading that they arise from something ending before the next oscillation has begun. The rest of the vapor, on the other hand, bears some relation to the arc lines which, by their indistinct beading and continuous background, show that they are associated with something persisting throughout and receiving fresh additions with each successive oscillation.

By allowing the light from the spark to fall first upon a plane grating, and then upon the rotating mirror an attempt was made to see if the spark lines extended only as far as the bright blue core and if they died out before the next oscillation. But for every metal tried, the spark lines in the visible spectrum were too close to the arc lines, and the image given by the mirror in rotation lasted too short a time to give any positive results in this connection.

This method of using a grating objectively and at the same time a mirror in rotation, did however show that the continuous spectrum is in the form of the irregular first discharge which extends across the spark-gap. (See Plate XIV, Fig. 1.) This figure also shows instead of one or two discharges as Schenck has observed (cf. p. 122) that there may be as many as six or seven discharges following the path of the first discharge.

The velocity of the streamers Schuster and Hemsalech found to be about 4×10^4 cm per sec. The order of the value obtained in the present investigation for the average velocity of the particles connected with the circular threads is 5×10^4 cm per sec.; and the close agreement between these two values led me to try to see if there were any relation between that part of the streamer measured by Schuster and Hemsalech, and the circular threads. It was thought that if an effect of the magnetic field upon the metallic vapor could be found, some relation between this vapor and the circular threads might be traced. Accordingly the oscillatory spark obtained with a capacity of 0.012 mf and a self-induction of 0.003 henries was made to pass in the strongest available magnetic field, in order to show whether the metallic vapor acts in a manner at all analogous to that characteristic of the brilliant circular threads occurring under conditions which are similar in every respect to the preceding except that less capacity is present in the discharge circuit. To obtain oscillations sufficiently separated for the study of the vapor just described a capacity of 0.012 mf was necessary, and this type of oscillatory spark showed no deflection in the magnetic field used for obtaining the circular threads. In a field of 12,000 units, however, the metallic vapor of this oscillatory spark was deflected into the form of broad, circular rings much like the circular threads, except that they were broad and not brilliant. It is possible that a much stronger field might introduce narrow, brilliant threads, just as an increase in the strength of the field introduced threads into the sheet of vapor belonging to the first type of spark. The brilliant blue core still remained close to the spark terminal at the two ends of each broad ring of vapor. If the magnetic field had caused any change in the core, this change would be difficult to detect because of the shortness of the core.

Photographs both in and out of the magnetic field were then taken with the mirror in rotation, in order to show whether the magnetic field produced a difference in the streamers. Both the bright core and the other vapor of the streamers showed irregularities when the spark was in the magnetic field, and these irregularities were such as a curved deflection might introduce into the motion of the particles giving the streamers. This suggested that the bright core, as well as the rest of the metallic vapor, was associated with charged particles, and additional evidence for this theory was afforded by the circular form of this vapor in a very strong field. If then every luminous part of the spark is associated with charged particles, Walter's theory that the arc lines are due to particles which have lost their charge seems doubtful. In whatever part of the spark the arc lines may originate, it seems probable that they must in any case arise from a luminescence excited by charged particles, since every part of the oscillatory spark suffers some deflection in the magnetic field, and this deflection obeys the electro-dynamic laws.

These arguments taken alone are, of course, insufficient to prove that the bright core seen in the third type of spark and the bright points of light seen in the first type of spark at the terminals have as their characteristic spectrum lines the spark lines and that the vapor envelope has the arc lines; but they give a definite support to the theory. Such a theory if proved would add weight to Schenck's suggestion that the spark lines are due to peculiar vibrations arising when the atoms are torn from the metal terminals, whereas the arc lines are due to the more fundamental vibrations which persist after the abnormal vibrations have died out.

BRIEF SUMMARY OF RESULTS

The three types of spark studied are described on p. 126.

1. When the spark is placed in a magnetic field, the direction of

which is parallel to that of the spark-gap, the first type of spark presents two sheets of vapor in the form of spirals. In the field at right angles to the spark length this vapor is in the form of two semicircular sheets, one being on each side of the spark-gap in a plane perpendicular to the direction of the magnetic field.

In the second type of spark (if the capacity did not exceed 0.002 mf) and in the third type of spark brilliant spiral threads in a parallel field and brilliant circular threads in a transverse field took the place of the spiral and circular sheets respectively. In the first and second types of spark the bundle of threads across the gap could not be deflected by a magnetic field of 12,000, the strongest to be obtained with the available amount of current, viz., 19 amp. In the third type the metallic vapor and the threads across the gap were deflectable in a very strong field and in a manner analogous to that of the circular and spiral threads.

The character of the deflection seems to furnish good reason to infer that the particles with which luminosity is associated possess an electric charge. A twofold asymmetry is present in the deflection of the circular sheets of the first type and of the circular threads of the second and third types, viz., an asymmetry as to the terminals and as to the width of the two sheets or sets of threads. Reversing the direction of the magnetic field, or that of the current through the primary of the inductive coil, changes the position of the sheets and of their ends. Decreasing the current through the primary, or lengthening the spark-gap sufficiently, causes one sheet, or set of threads to disappear.

2. The circular sheet of the first type of spark gives the spectrum of the nitrogen bands. The central threads show that of the metallic lines and the air lines.

The second type gives the same spectrum for the bundle of central threads as for the circular threads, viz., that of the very bright air lines and the fainter metallic lines.

In the third type of spark the central threads show the same spectrum lines for each of the seven different metals which were used as spark terminals, these lines being identified with the air lines.

The spectrum of the circular threads shows the arc lines in addition to the air lines.

The spectrum of the part of the spark about the terminals shows the spark lines in addition to the arc and air lines. This gives the combined spectra of the metallic vapor, the circular and the central threads, because the metallic vapor could not be isolated.

These facts, together with certain observations presented at the end of this paper, give further evidence that the spark lines may be due to abnormal vibrations arising when the atoms are torn from the metal terminals; whereas the arc lines in the spark spectrum may be due to the more fundamental vibrations.

3. The value of the velocity of the particles associated with the circular threads is approximately 5×10^4 cm per sec. and this velocity is of the same order as that obtained for the streamers when they are measured close to the spark terminals.

These particles carry a negative charge.

They move in paths of different curvature.

Substituting in the equation

$$\rho=\frac{mv}{eH}$$

the values found for their velocity and for the curvature of their paths, $\frac{e}{m}$ is found to vary from 1.2×10^2 to 0.7×10^2.

The present investigation seems to show that in the electric discharge at atmospheric pressure there are negative particles which in a magnetic field describe luminous paths in the form of spirals and circles, similar to those described by the negative particles emitted by a hot lime cathode[1] in the discharge at low pressure.

The velocity of these particles in the discharge at atmospheric pressure is of the order of 5×10^4 cm per sec. whereas that of the particles in the discharge at low pressure is from 1.6×10^8 cm per sec. to 1.07×10^9 cm per sec.

It does not follow that these negative particles at atmospheric pressure are themselves luminous. The bright spiral and circular paths seen in a magnetic field may mean simply that the particles excite to luminescence the gas through which they pass. The nitrogen bands which constitute the spectrum of the spiral and circular sheets in the first type of spark seem to indicate either that the nega-

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[1] Wehnelt, *loc. cit.*

tive particles associated with these sheets are capable of exciting a luminescence in the gas through which they pass, but have no luminescence of their own, or that the particles of air have themselves become ionized as well as excited to luminescence. The arc lines, however, which appear in addition to the air lines in the spectrum of the third type of spark, suggest that the charged particles here not only bring to luminescence the gas through which they pass but also that they themselves emit a radiation characteristic of the metal from which they appear to come.

The average velocity of the particles associated with these circular threads seems to be of the same order as that of the metallic vapor, as long as the latter is still close to the spark terminals. This agreement of the velocities and further the fact that the arc lines are present in the spectra of both the threads and the vapor, suggest some analogy between them.

Little that is definite can be said about the central threads. In the first and second types of spark they could not be deflected with a magnetic field up to 12,000, whereas in a field of this strength the central threads in the third type of spark assumed the form of spirals and semicircles, having a radius so small that measurements like those of the easily deflected threads were impossible. Thus far the spectra of these threads in the third type of spark give no clue to the nature of their mechanism.

The present investigation was suggested by Professor W. B. Huff, of Bryn Mawr College. I wish to acknowledge my indebtedness to him and to Dr. James Barnes, of Bryn Mawr College, for their helpful suggestions and criticisms during the course of the investigation.

Physical Laboratory
Bryn Mawr College
March 1908

DESCRIPTION OF PLATE

Fig. 1.—Oscillatory spark taken with the mirror in rotation. Speed of mirror —50 revolutions per sec., C=.012 mf., L=.003 henries. The lower figure shows the first discharge and six weaker discharges (*a*) which follow approximately the same path; also the short, curved streamers (*b*). The upper figure shows the trailing light (*c*). If the spark passes when the mirror is in exactly the right position, all these features may be seen in the same spark-discharge. P. 122.

Fig. 2.—Spirals. Spark-length parallel to the magnetic field. *Al* terminals. P. 127.

PLATE XIV

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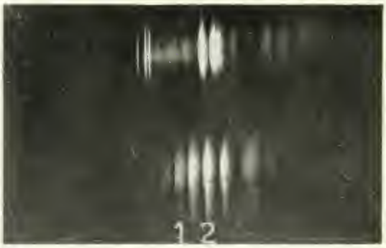
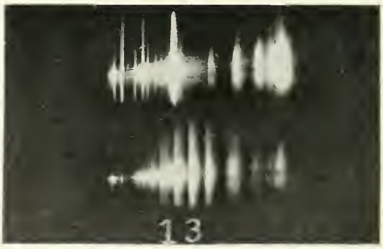

12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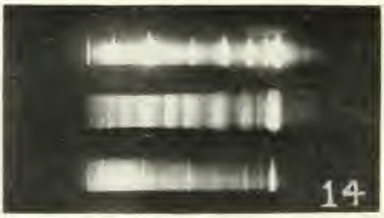
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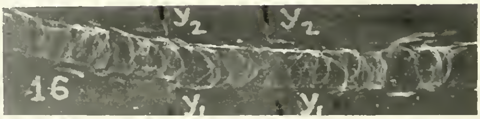

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FIG. 3.—Circles. Spark length perpendicular to the magnetic field. The shape of the terminals did not permit complete semicircles below. P. 127.

FIG. 4.—Oscillatory spark with terminals too widely separated for the presence of the circular threads. It shows the vapor about the terminals and the irregular, central threads. P. 128.

FIG. 5.—Spark with a capacity of 0.0005 mf and no self-induction. It shows the bundle of bright threads straight across the spark-gap and the circular threads on one side of the gap. To the eye they were also present on the other side, but the short exposure of 1/50 sec. evidently "caught" the spark at an interval when they were present on one side only. Pp. 128 and 129.

FIG. 6.—Spiral form of the central threads in the oscillatory spark ($C=0.012$ mf, $L=0.003$ henries). The radius of curvature is too small for them to appear clearly in the photograph. P. 130.

FIG. 7.—To show the twofold asymmetry in the circular threads. Pp. 129, 131, and 132.

FIG. 8.—Asymmetry of sheets. Pp. 131 and 132.

FIG. 9.—Circular threads present only on one side of the spark-gap. P. 132.

FIG. 10.—Same, but direction of magnetic field reversed. Pp. 131, 132, and 133.

FIG. 11.—Same as 8 but direction of current through the primary reversed. This shows the bright points of light where the sheet meets the terminals. In figs. 8, 10, 11, on the left-hand side the sheets are partly hidden by the spark terminal. Pp. 131, 132, and 133.

FIG. 12.—Lower spectrum, that of the sheet in the first type of spark, taken with the outer edge of the sheet focused upon the slit. Upper spectrum that of spark, obtained with C, and L in the circuit, taken for purposes of comparison. *Cd* terminals. These spectra are not in focus on the right owing to the plane surface of the photographic plate. P. 134.

FIG. 13.—Lower spectrum that of the central threads and sheet of the first type of spark taken close to the terminal. Upper spectrum that of the spark, obtained with C and L in circuit, taken for purposes of comparison. *Mg* terminals. P. 134.

FIG. 14.—Spectra of three different parts of the oscillatory spark ($C=0.002$ mf, $L=0.003$ henries). Upper spectrum that of the metallic vapor, central threads, and circular threads, taken close to the spark terminal. Central spectrum that of the circular threads. Lower spectrum that of the central threads, taken in the center of the spark gap with terminals so far apart that center was free from metallic vapor. *Mg* terminals. P. 136.

FIG. 15.—Spectra of central threads of oscillatory spark taken in the following order from the top of the figure: *Al, Mg, Zn, Cd, Ca, Bi.* P. 136.

FIG. 16.—To show the images of the circular threads, secured with the mirror in rotation, upon which the measurements of the velocity of the particles associated with the circular threads were made. P. 138.

FIG. 17.—Spectrum of the spark ($L=0.0015$ henries) of magnesium taken with the spark length parallel to the slit of the spectroscope. P. 143.

ON THE ORBITAL ELEMENTS OF *ALGOL*

By R. H. CURTISS

It has long been known that the interval between successive light-minima of *Algol* varies minutely and irregularly. But as to the character of these inequalities little was recognized until 1888, when Chandler showed them to be closely represented by an empirical periodic expression involving three sine terms with periods of one hundred and thirty, thirty-five, and sixteen years. To account for the long-period term, which in its influence greatly transcends the others, Chandler postulated a third mass entering into a system about whose center of mass the eclipsing pair revolves in an orbit similar in size and form to that of *Uranus* in a period of 130 years. To account for the remaining inequalities he further suggested the presence in the system of a fourth body. In 1894 Bauschinger showed that Chandler's corroborative evidence based on variations in the proper motion was apparently illusory; and in the following year Tisserand proposed the alternative hypothesis that the long-period inequalities in *Algol's* minima are due to a revolution of the line of apsides of the slightly eccentric orbit of the eclipsing stars in a period of one hundred and thirty years, this revolution being attributable not to a third body but to a reasonable oblateness of the brighter star. Tisserand's value for the eccentricity (0.12), as well as the variations in duration of diminished brightness demanded by his hypothesis, are only approximately in accordance with the results of observation. There still remains a third possible hypothesis which postulates a third body relatively close to the eclipsing pair. In such a system perturbations arising from the mutual attraction of three bodies, of which one or more are probably oblate, could probably account for all irregularities observed in *Algol's* light-minima. It was to examine the evidence contained in recent radial velocity observations bearing upon these hypotheses, as well as to develop data for the guidance of spectroscopic observers in future work, that the following investigation was undertaken.

THE VELOCITY OF THE CENTER OF MASS OF THE ECLIPSING SYSTEM

The element whose variations bear most directly on the above hypotheses is the velocity of the eclipsing system. In 1906 Belopolsky assembled the five known values of this quantity and concluded that the observed variation of 15 km might not be real. At that time there had been published about 90 determinations of *Algol's* velocity taken in eight seasons, making an average of only eleven plates per season. Subsequently 157 measures of *Algol's* velocity in the seasons of 1905–6 and 1906–7 have been published by Belopolsky, Schlesinger, and the writer. From his own results Belopolsky concludes that "the above material does not as yet suffice for a determination of variations in the radial velocity of the system. Possibly that variation lies in the appearance of the spectrum lines; for example, in the unsymmetrical maxima found in them." But with the addition of independent evidence from 93 plates made at Allegheny Observatory and grouped about two epochs 0.3 years apart there seems good justification for an investigation of the data.

In Table I, I have assembled all the results of published data bearing on the center of mass velocity of the eclipsing system of *Algol*. In the first column appears the epoch of each set of plates formed by taking the mean of the dates of the plates involved. With

TABLE I

OBSERVED VELOCITIES OF THE CENTER OF MASS OF THE ECLIPSING STARS OF *Algol*

Epoch	Velocity	Systematic Reduction	Curvature Correction	Corrected Velocity	No. of Plates	Observers
	km	km	km	km		
1888.99	− 0.2	+5.2	±0.0	+ 5.0	3	Vogel and Scheiner
1889.94	± 0.0	+5.2	±0.0	+ 5.2	6	Vogel and Scheiner
1890.90	− 4.2	+5.2	±0.0	+ 1.0	3	Vogel and Scheiner
1897.80	− 2.0	±0.0	−0.1	− 2.1	24	Belopolsky
1898.73	+ 9.7	±0.0	±0.0	+ 9.7	8	Belopolsky
1902.94	+11.0	±0.0	+0.3	+11.3	20	Belopolsky
1903.90	− 4.0	±0.0	−0.2	− 4.2	15	Belopolsky
1905.01	+12.5	±0.0	+0.1	+12.6	14	Belopolsky
1906.06	+ 2.0	±0.0	±0.0	+ 2.0	23	Belopolsky
1906.82	+12.1	−0.9	+0.2	+11.4	44	Curtiss
1906.82	+ 7.5	+4.0	+0.2	+11.7	41	Schlesinger
1906.98	+ 6.5	±0.0	±0.0	+ 6.5	45	Belopolsky
1907.10	+ 3.9	−0.9	±0.0	+ 3.0	48	Curtiss
1907.11	− 1.7	+4.0	±0.0	+ 2.3	45	Schlesinger

the exception of the Allegheny observations each epoch corresponds to the plates for any one season. In the case excepted the observations naturally group themselves into two periods of two and three months each. Column 2 contains the values of the velocity of the system determined as described below. Columns 3 and 4 contain corrections necessary to reduce the velocity observations to homogeneity and are described below. Column 5 contains the final adopted values of the velocities. Column 6 gives the number of plates in each epoch and column 7, the observers' names.

PREPARATION OF OBSERVATIONS

Epochs 1888.99, 1889.94, and 1890.90.—For the determination of the center of mass velocity at these three epochs the final elements of Belopolsky based upon 117 observations of the years 1902–7 were accepted as standards. After eliminating the center of mass velocity the curve corresponding to these elements was accurately drawn on a large scale and the residual from that curve for each of the 1888–91 observations was graphically determined. The mean of the residuals for all the plates of each epoch was adopted as the velocity of the system for that epoch. In view of the suspected variation of some of the elements of the orbit of the eclipsing pair, errors may arise from this procedure which, since the observations do not suffice for independent determinations of eccentricity at these epochs, I have considered it best to adopt. Justification for this course seems to be ample in view of the character of the resulting residuals. But a further check is furnished by an independent value of +0.7 km for the center of mass velocity from the six observations of 1889–90 obtained by passing a smooth curve through them. Still further corroboration is afforded by Vogel's value of −3 km obtained from all twelve plates, agreeing with the mean of my three values within the limits of error. The treatment of the data is fully exemplified in the following Table II.

Epoch 1897.80.—The observations for this epoch were fully reduced by Belopolsky, whose value of the velocity of the system is here adopted.

Epoch 1898.73.—These eight observations of the fall of 1898 were not strong enough to determine a velocity-curve. They were

TABLE II

Determination of Radial Velocities of Center of Mass for Epochs 1888.99, 1889.94, and 1890.90

Date	Phase	Velocity	Residual from Standard Curve
	year	km	km
1888, December 4	0.518	−38.9	±0.0
1889, January 6	1.937	+31.4	−4.7
1889, January 9	2.061	+43.9	+4.0
			Mean −0.2
1889, November 13	0.562	−38.9	+1.3
November 23	1.945	+38.2	+1.6
November 26	2.056	+38.0	−1.8
1889, December 21	1.147	−28.7	−3.4
1890, January 1	0.666	−40.4	+2.0
1890, January 3	2.656	+20.5	±0.0
			Mean ±0.0
1890, September 13	0.692	−43.8	−1.4
1890, October 13	1.976	+34.5	−3.7
1891, March 17	2.126	+35.6	−7.6
			Mean −4.2

reduced in the same manner as those of 1888–91. But the residual for each plate was determined not only from the 1902–7 elements of Belopolsky but also from the elements of 1897–8, with the velocity of the center of mass eliminated. The data are fully shown in Table III. In the final mean the results obtained from the two sets of elements were given equal weight. That the result obtained by using the elements of 1897–8 does better satisfy the final curve seems to be accidental in view of the character of the residuals in each case.

Epochs 1902–5.—For these three epochs I have adopted the mean of the two values published by Belopolsky in the *Mitteilungen der Nikolai-Hauptsternwarte zu Pulkowo*, Band **1**, No. 8, and Band **2**, No. 22. There is some probability that several plates of October, 1905, were included in the first reduction of the 1904–5 series, but as Belopolsky's two values for this epoch differ by one kilometer only, I have thought it safe to use the direct mean.

Epochs 1906.06 and 1906.98.—Belopolsky's published values were here adopted from the publications above cited.

TABLE III

Reduction of 1898 Observations for Determination of the Velocity of the Center of Mass

Date	Phase	Velocity	Residuals from Elements of 1902–7	Residuals from Elements of 1897.80
		km	km	km
1898, September 13........	0.997	−20	+15	+16
14........	1.969	+49	+11	+ 6
16........	1.068	−25	+ 6	+ 9
17........	2.089	+36	− 6	−12
19........	1.258	+10	+26	+34
25........	1.511	+11	+ 7	+17
October 3........	0.880	−17	+22	+21
4........	1.930	+29	− 7	−10
Means............			+9.3	+10.1

Epoch 1906.82.—In this case the observations of Dr. Schlesinger and he writer were treated separately. The velocity of center of mass of each observer expressed in the final elements was reduced to the epoch 1906.82 by applying an additive correction of 9.2 km in Dr. Schlesinger's case and 8.7 km in my own. These corrective terms were in each case the weighted mean of the residuals of the plates included in this epoch from the curve corresponding to the final elements.

Epoch 1907.10 and 1907.11.—In this case the velocity of center of mass of the final elements was reduced to the epoch of the plates by applying the corrections ±0.0 km for Schlesinger and −0.5 km for Curtiss, determined as in the above case by forming the weighted means of the residuals for each plate of this epoch from the curve of the final elements.

The systematic differences.—Column 3 of Table I contains the quantities necessary to reduce the observations made at Potsdam and Allegheny to homogeneity with those made at Pulkowa. In each instance the reduction to Belopolsky's zero was obtained from these observations themselves since such corrections were undoubtedly a function of the spectral type. For the Allegheny observations the systematic differences were evident at once, since the plates were contemporaneous with Belopolsky's series. For the Potsdam observations it was found, by applying the period obtained from the other measures, that these three early velocities formed a definite group which could be reduced to the curve only by the application of a definite systematic correction. In seeking confirmation of this difference between Belopolsky's velocities for this stellar type and the early Potsdam results, I have employed the immediately available data contained in Scheiner's *Astronomical Spectroscopy* and Frost and Adams' paper on "Radial Velocities of Twenty Stars of the *Orion* Type." Since from the plates of *Algol* and from my own unpublished measures of *β Orionis* I am aware that the measures of Belopolsky, Frost, and myself are in close agreement, I have in the following Table IV compared directly the measures of Frost and Adams and of Vogel and Scheiner. A comparison for *a Andromedae* was taken directly from the *Publications of the Allegheny Observatory*, Vol. I, No. 3.

TABLE IV

Star	Frost and Adams' Velocity	Vogel and Scheiner's Velocity	Difference
	km	km	km
β Orionis......................	+20.7	+16.4	+4.3
γ Orionis......................	+18.0	+ 9.2	+8.8
ε Orionis......................	+26.5	+26.7	−0.2
ζ Orionis......................	+18.3	+14.8	+3.5
	Baker's Velocity		Mean +4.1
a Andromedae.................	+17	+5	+12
Algol.........................	Belopolsky's Velocity − Vogel and Scheiner's		+5.2

In determining these systematic differences in the case of *Algol* I have not noted any certain effects due to the change of optical parts at Pulkowa and Allegheny during the observations.

Corrections for curvature.—In deriving the first values of the velocities of Table I it was in each case assumed that the value for the velocity of the system contained in the elements corresponded to the mean of all the dates. This assumption was justified when the observations extended along a nearly straight section of the curve, but near turning-points it was thought desirable to avoid the approximations involved in the above assumption by applying corrections depending upon the departure of the curve from a straight line. This small correction for curvature for any set of plates was derived with sufficient accuracy from one of the trial velocity-curves of the center of mass by estimating on the graph the point representing the mean of the center of mass velocities corresponding to the plates in that set of observations assumed to be uniformly distributed on the section of the curve over which they extended. The residual of this point from the curve was adopted as a correction for curvature for this set of plates. The application of this correction increases the double amplitude of the final curve about 0.5 km but has no appreciable effect upon the period. The curvature corrections are given in column 4, Table I.

Determination of elements.—A preliminary study of the center of mass velocity observations since 1900 led to the assumption of the following circular elements: epoch of minimum velocity, 1902.3; period, 1.73 years; double amplitude, 19 km; velocity of three-body system, +4.3 km. These elements satisfied the later observations fairly well, but when it was attempted to extend them they were found to be inconsistent with the early Pulkowa and Potsdam measures. It was found, however, that the early Pulkowa measures could be brought approximately to the curve with periods of 1.54, 1.62, 1.90, and 2.07 years, and that the Potsdam observations could be adjusted roughly to the curve with periods of 1.62, 1.71, 1.81, 1.90, and 2.03 years. It was also evident that, of the values of the period which were roughly consistent with all the earlier measures, but two values, viz., 1.62 and 1.90 years, could also represent the later observations satisfactorily. Accordingly the first value of the period was studied and the following elements derived: epoch of minimum velocity, 1902.5; period, 1.624 years; double amplitude, 20 km; velocity of system, +6 km. As the residuals resulting from these elements were unwarrantably large the alternative value of 1.90 years was tried. From a study of all the observations on this basis during which some eight different sets of circular elements were tested, I have derived the following constants of the orbit of the center of mass of the eclipsing system of *Algol:*

E (epoch of minimum velocity)	1901.850 years
P (period)	1.899 years
$A=B$ (single amplitude of curve)	9.4 km
C (center of mass velocity)	+4.1 km
$R \sin i$ (the projected radius)	89,000,000 km
μ (mean yearly motion)	189°.6

The velocity-curve corresponding to these elements together with all the observations of *Algol's* center of mass velocity are graphically represented in the accompanying diagram. Observations represented by single, double, and triple circles were determined from less than 20 plates, from 20 to 40 plates, and from over 40 plates, respectively. In the following table (V) is shown a comparison of the observed and computed velocities on the basis of the above elements. As a result of the numerous trials made with various sets of elements, I am inclined to think that the uncertainty in *E, P, A,* and *C* is not greater than 0.05 years, 0.01 years, 0.7 km, and 0.5 km respectively.

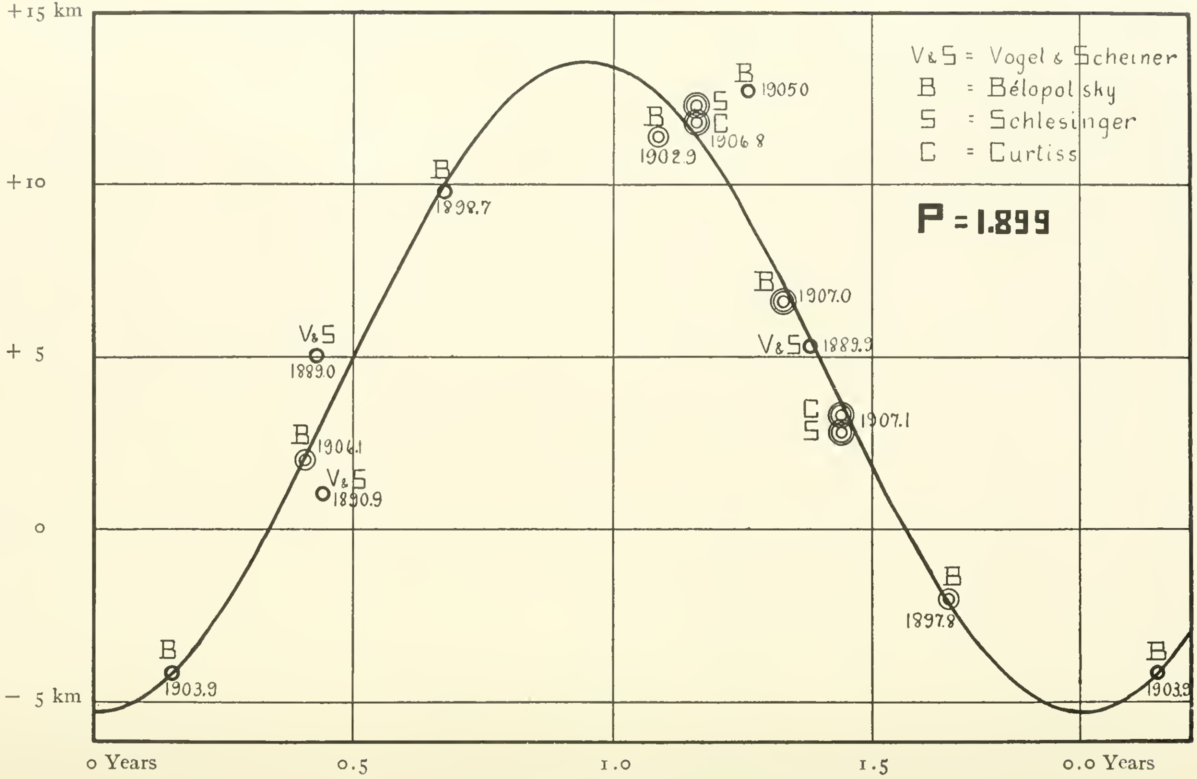
TABLE V

COMPARISON OF OBSERVED WITH COMPUTED VELOCITIES

Epoch in Years	Phase Referred to Minimum Velocity	Observed Velocity	Computed Velocity	Residuals	Number of Plates
	Years	km	km	km	
1903.90	0.15	− 4.2	− 4.2	±0.0	15
1906.06	0.41	+ 2.0	+ 2.1	−0.1	23
1888.99	0.43	+ 5.0	+ 2.7	+2.3	3
1890.90	0.44	+ 1.0	+ 3.0	−2.0	3
1898.73	0.68	+ 9.7	+10.0	−0.3	8
1902.94	1.09	+11.3	+12.5	−1.2	20
1906.82	1.17	+11.4	+11.1	+0.3	44
1906.82	1.17	+11.7	+11.1	+0.6	41
1905.01	1.26	+12.6	+ 9.0	+3.6	14
1906.98	1.33	+ 6.5	+ 7.0	−0.5	45
1889.94	1.38	+ 5.2	+ 5.5	−0.3	6
1907.10	1.45	+ 3.0	+ 3.3	−0.3	48
1907.11	1.46	+ 2.3	+ 3.0	−0.7	45
1897.80	1.65	− 2.1	− 2.3	+0.2	24

DEDUCTIONS FROM THE STUDY OF *ALGOL'S* CENTER OF MASS VELOCITY

The agreement of the above sine curve with observation furnishes strong evidence of a periodic variation in the center of mass velocity of *Algol's* eclipsing system. And the character of this variation is such as to render probable the theory that a revolution of this system in a period of 1.9 years is taking place about a center distant from it not less than 89,000,000 km. It is also probable that the orbit of the center of mass of the eclipsing pair is nearly if not quite circular, and that at least three masses are involved in the system, two of which are extremely close while the third is at a distance comparable with the earth's distance from the sun, unless the mass of the third



Velocity Curve of *Algol's* Center of Mass body be relatively small. If the mass of the third body be not relatively small, perturbations of the elements of the eclipsing pair would naturally arise, and by such perturbations as well as by effects due to the oblateness of one or more of the stars the known variations in the period of *Algol's* eclipse may be accounted for. Tisserand has shown that a rotation of the line of apsides of the close stars in a period of 130 years, would explain the long-period term in the variations of *Algol's* light-minima if the eccentricity of the orbit be 0.12. It can also be shown that a variation of 0.10 in the eccentricity of the orbit of the close stars can give rise to variations of an hour or more in the times of light-minima. Such perturbations seem consistent with the probable character of the system, though further studies both theoretical and observational are necessary to supplement the evidence furnished by the light-variations. If, however, the above orbital motion of the close system is admitted, there must result a periodic variation in the time of light-minima with a range of ten minutes and a period equal to the orbital period of 1.9 years. That such a variation was not brought out by Chandler is not surprising, since his mean epochs were separated by intervals of from 1 to 4 years, a procedure that would probably conceal a short-period term of small amplitude. It may not be merely accidental, however, that Chandler's fifteen-year term has a period of eight times the above and a range of 7 minutes. The writer hopes in the future to be able to examine photometric observations for the existence of this two-year period.

THE ELEMENTS OF THE ORBIT OF THE ECLIPSING PAIR

In order to adduce all the data bearing upon the variations in *Algol's* light-period and to show at a glance the present condition of our knowledge of the more difficult orbital elements, Table VI has been formed.

It may be seen that little can be derived from a study of these elements at present. There seems to be no evidence of variation in $a \sin i$ greater than the limits of accuracy of the determination; and the values of the longitude of periastron are too erratic to make possible any deductions from them. There is a chance of a variation of about 0.10 in the eccentricity and if, as seems to be the case,

TABLE VI

Elements of the Orbit of the Brighter Star of *Algol*

Epoch	e	ω	$a \sin i$	Observers
1889.9	0.0±	....	1,617,000 or 1,707,000	Vogel and Scheiner
1897.8	0.11	4°	1,663,000	Belopolsky
1902.9	0.14	....	1,630,000	Belopolsky
1903.9	0.09	....	1,650,000	Belopolsky
1902.5	0.13	69	1,620,000	Belopolsky
1905.0	0.07	....	1,640,000	Belopolsky
1902.7	0.05	42.5	1,694,000	Belopolsky
1907.0	0.05	21	1,600,000	Schlesinger and Curtiss

e was about 0.0 at the epoch of 1890, the period of this variation would seem to be about 15 years, or about that of Chandler's short period. If the longitude of periastron is in the neighborhood of 45°, as determined by Belopolsky from his observations of 1902–7, the variation in the light-period resulting from such a variation in e would be much greater than Chandler's 15-year period could account for. Probably then, if the variation in e is real, the true value of the element (ω) is at present nearer 0° or 90° than 45°. That no more definite deductions are possible after twenty years of spectrographic obervations of *Algol* emphasizes the need for more extensive investigation of this star.

In conclusion it is of interest to consider the bearing of further observations on the velocity-curve of the center of mass, assuming that the elements of this paper are correct. The determination of the present season will follow along the ascending limb of the curve where observations are needed. In following years the observations will alternate between the two limbs of the curve until twelve years have elapsed, when they will reach the maximum and minimum of the curve and complete its accurate determination. The importance of the determination of as many epochs as possible by each observer in a season is obvious. And when a long series of observations are combined into one epoch, corrections for the varying radial velocity of the eclipsing system's center of mass should be applied to each plate, since this term is quite comparable with that arising from the earth's orbital motion. Possibly it would now be of value to again reduce the observations already made, eliminating the varying center of mass velocity for the better determination of e and ω.

The results of this paper may be summarized as follows: The known values of the velocities of the center of mass of the eclipsing system of *Algol* are found to vary with the time in such a way as to satisfy a sine curve with a period of 1.899 years. The amplitude of this curve is 9.4 km. The velocity was a minimum at the date 1901.85. The circular orbit corresponding to this sine curve has a radius of not less than 89,000,000 km and the center of this orbit is moving with a velocity of +4.1 km in the sight-line.

The mutual attraction of the three bodies which apparently enter into the system can probably account for the variations observed in the light-period.

As a consequence of this orbital motion of the center of mass of the eclipsing pair, a variation of ten minutes in the time of light-minimum with a period of 1.9 years should be shown by photometric observations.

Examination of the published elements of *Algol* suggests a possible change in the eccentricity. But our present knowledge is too meager to permit any certain deductions regarding such possible variations.

Detroit Observatory
May 1908

NOTE ON THE WAVE-LENGTH OF $H\delta$ AND $H\epsilon$ IN THE SOLAR SPECTRUM

By J. EVERSHED

The wave-length of the hydrogen line δ given in Rowland's Preliminary Table of wave-lengths in the normal solar spectrum, viz., 4102.000, has been previously called in question, since it does not agree with measures of the line obtained from vacuum tube discharges in hydrogen nor with measures of the bright line in *o Ceti*. According to Jewell, however, the position given in the table is most probably correct, taking into consideration the complicated structure of the line, due to the presence of other absorption lines.[1]

That the line should deviate in the sun from its theoretical position in the series, and from its position in terrestrial sources, by an amount so large as 0.10 Å., seems very improbable, the more so since it is now known how very closely the ultra-violet members of the series, as far as they can be photographed at eclipses, accord with the values derived from Balmer's formula. It seemed to the writer, therefore, desirable to get some measures of the emission line in the chromosphere, where the presence of interfering lines would have practically no effect. Accordingly in May 1907 a spectrograph was arranged for photographing $H\delta$ at the sun's limb.

A preliminary difficulty presented itself in the diminishing intensity of the hydrogen lines toward the ultra-violet, and the consequent rapidly diminishing height above the photosphere at which the lines can be photographed, as bright lines, under ordinary circumstances. In the case of $H\delta$, with a tangential slit at the sun's limb one obtains a broad bright line, corresponding with the lower region of the chromosphere, and even this is easily obliterated by a slightly diffusive sky, or by unsteadiness in the image. Probably it would be possible to photograph $H\delta$ as a narrow line in the brightest prominences, but possible motion in the line of sight in these would vitiate any measures of wave-length. It was found, nevertheless, that by placing the slit slightly within the limb, the bright line is still visible, but with the

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[1] *Astrophysical Journal*, 9, 211, 1899.

narrow absorption lines superposed. This absorption line is fairly easy to measure, being free from interfering lines; and since the lines used as standards in the determinations of wave-length are due to the photospheric spectrum in the same locality as the hydrogen, motion in the line of sight due to rotation is eliminated. Recognizing, however, the possibility that the higher chromosphere might rotate at a speed differing from that of the underlying reversing layer, it was thought best to make a series of exposures on both east and west limbs, taking finally the mean values obtained from both. These mean values would still be subject to a small positive correction due to the shift of the low-level lines at the limb toward the red, discovered by Halm, which in all probability will not affect the hydrogen lines, at any rate to the same extent.

The spectrograph I employed consists of a plane grating, with 14,428 lines to the inch, and a ruled surface 3.2 inches in length. The collimator has a 3¼-inch visually corrected lens of 36 in. (914 mm) focal length; and a single plano-convex lens of 101 mm (4 in.) aperture and 213 cm (7 ft.) focus for *Hδ* is used for the camera. The instrument is used in connection with the 12-inch Cooke photo-visual lens of this Observatory, which gives an image of the sun about 60 mm in diameter. The best results were obtained in the fourth order, notwithstanding the long exposures needed, and most of the plates obtained include, besides *Hδ*, the lines *Hϵ*, H, and K. They are on a scale of 1 mm = 1.9 Å., approximately. Recently it has been found better to use the grating in the position to give greater magnification, as in this way the full photographic resolution can be realized with the greatest economy of light, and without increasing the length of the camera.

The results obtained from the few plates selected for measurement last year are not sufficiently numerous or accordant to give a really good value for the wave-length of *Hδ*; but they show nevertheless, I think conclusively, that the line does not differ appreciably from its theoretical position. A few measures have also been obtained from spot spectra, where the line seems always to be narrowed, and in many cases is very much weakened: these measures confirm the others in showing that Rowland's value, 4102.000, must certainly be erroneous.

In the following table I give the values of *Hδ* separately for the east and west limbs. The measures were made with a Hilger micrometer microscope, having a screw of 1 mm pitch, and reading to 0.01 mm, and by estimation to 0.001 mm. Each determination is a mean of two separate measures, in which the end of the spectrum toward the red was placed to the right and left respectively. The lines used as standards are the iron lines given in Rowland's table at 4100.315, 4100.901, 4101.421, 4104.288, and the line at 4103.097 attributed to silicon and manganese.

TABLE I

$H\delta$ Absorption Line

Date 1907	East Limb		West Limb	
	Latitude	Wave-Length	Latitude	Wave-Length
May 18...........	−13°	4101.88	+12°	4101.89
May 18...........	−10	.89	+ 7	.91
May 18...........	− 8	.92	− 8	.90
May 19...........	+ 8	.91	−10	.91
May 19...........	+10	.90		
May 20...........	+ 9	.88	− 8	.91
May 30...........			+14	.90

Mean, east, 4101.897; mean, west, 4101.903; mean of east and west, **4101.900**; mean width of emission line, 0.62; of absorption line, 0.29.

In spot spectra the line shows a tendency to be displaced to the violet, which in some instances is very marked. In the spot of July 16, 1907, $H\delta$ is displaced about 0.05 to the violet, while $H\gamma$ is apparently in the normal position. It is to be remembered that the absorption lines in the two cases may represent different levels in the chromosphere. In the following measures the iron lines in the spot spectra were used as standards. Any displacements therefore are relative to the spot lines, and not those of the sun. No measurable displacements were detected, however, in the reference lines of the spot spectra, compared with those of the neighboring photosphere.

Three spot spectra photographed with the 18-ft. grating spectrograph at Mount Wilson in November 1906 give respectively .	4101.897
	.883
	.839
Spot spectra photographed at the Kodaikanal Observatory:	
Large spot, 1907, June 20	4101.821
Same spot, 1907, June 22	.868
Spot of 1907, July 16	.866

The rather large deviations in the separate measures in Table I are not due to errors of measurement, but are probably partly accounted for by the disturbing effect of a bright sky on the position of the reference lines. This is almost certainly the case with the plate of May 18, latitude -13° east. In this image the chromospheric lines δ, ε, H, and K are very strong as bright lines, but the Fraunhofer lines are weak, and are probably partly due to skylight. Rotation displacement will therefore affect the measures to some extent. In the mean values the west limb seems to give a slightly larger wave-length than the east, which would indicate a greater rotational speed for hydrogen compared with the reversing layer. But as the influence of the sky spectrum would tend in this direction it would be unsafe to draw this conclusion without further evidence. In the plate of May 20, however, in which the east and west spectra are photographed side by side, the evidence of a forward drift of the hydrogen and calcium over the gases of the reversing layer seemed so clear when direct measurements of the displacements were obtained, and the measures were extended to H and K, that it was decided to make a separate investigation to determine whether this was a normal condition or merely a local drift of the higher chromosphere. I give in a subsequent paper some of the results of measures made on plates in which the two limbs are photographed simultaneously.

The line *Hε* is easily photographed as a bright line, as it comes under the protection, so to speak, of the broad shading of H, but in only one instance have I found any trace of an absorption line, and this was too faint for measurement. In the measures the broad line was bisected, and the edges, which are well defined, were also measured, the mean of the two edges being used to correct the central bisections. The measures with the less refrangible end of the spectrum placed to the right and left respectively show a greater degree of accordance than those of *Hδ*, and in Table II, I retain the third decimal figure, since the mean error for each determination is well below 0.005 Å. The lines used as standards are the iron lines in Rowland's table at 3960.422, 3965.655, 3969.413, 3971.475, and 3977.891; and in one plate the aluminium line at 3961.674 was used.

Excepting the west limb spectrum of May 20, which gives abnormally large values for all the four chromospheric lines (δ, ε, H, and K),

TABLE II

*H*ε Emission Line

Date 1907	East Limb		West Limb	
	Latitude	Wave-Length	Latitude	Wave-Length
May 18...........	−13°	3970.222	+12°	3970.200
May 18...........	−10	.219	+ 7	.195
May 18...........	− 8	.220	− 8	.203
May 19...........	+ 8	.215	−10	.204
May 19...........	+10	.220		
May 20...........	+ 9	.213	− 8	.229
May 30...........			+14	.201

Mean, east, 3970.218; mean, west, 3970.205; mean of east and west, **3970.212**; mean width of emission line, 0.52.

the values for the west limb are all smaller than those for the east, the mean diffeernce, excluding May 20, being 0.018 Å. The displacement is in the opposite direction to that shown by *H*δ in Table I, but this apparently anomalous behavior of the two hydrogen lines receives a probable explanation when we consider the conditions in photographing a bright chromospheric line like ε, and a dark reversal of a bright line as in δ. In the former case, we have an angular separation amounting to several seconds of arc between the source of the bright line and that of the dark lines to which the measures are referred; and a slit of finite width. A consideration of the subjoined diagram will show that the displacement due to this cause may amount to half the slit-width × the ratio of the focal lengths of collimator and camera, when the bright radiation extends outward from the photosphere with uniform intensity for a distance equal to, or greater than, the slit-width.

In the diagram, *LL* represents the position of the sun's limb during an exposure, *S* is the opening of the slit greatly magnified, while the dotted line represents the upper limit of the chromospheric radiation, the photosphere being on the opposite side of *LL*. It is evident that whatever position the limb may occupy within the opening of the slit, provided it remains stationary during the exposure, the spectral images of the photosphere and chromosphere will be displaced relatively by half the slit-width, and this of course will be increased in proportion as the length of the camera exceeds that of the collimator. Obviously a dark reversal on a broad bright line will not be subject to this displacement, as the source of the reversal is the same as the source of the reference lines. It will, however, be unsymmetrically placed on the bright line.

In the spectrograph I employed the optical parts were so arranged that the east limb was on the more refrangible side of the spectral images of the slit. The width of slit used was 0.05 mm, and the camera magnified 2.3 times: therefore, under the ideal conditions of perfect steadiness of the sun's limb represented in the diagram, and uniform intensity in the chromospheric radiation, there would be a linear displacement of $0.025 \text{ mm} \times 2.3 = 0.057$ mm, equal to 0.108 Å., with the dispersion employed. This would be in the direction which would increase the east limb values, and decrease those of the west limb. In the actual case of an unsteady image, the whole slit may be illuminated many times in succession by both photosphere and chromosphere during an exposure, and this tends to bring the chromospheric lines to their normal positions with respect to the photospheric lines. Also the ϵ radiation does not extend uniformly to any considerable height, the effective portion of the light coming from a very low level. That the actual displacement found is only one-sixth of the value deduced above is not therefore at all surprising.

Although no significance, therefore, can be attached to the apparent displacement of $H\epsilon$ at the two limbs, the mean value of east and west will be entirely free from this source of error.

I give finally in Tale IV a comparison of the principal hydrogen lines in the sun, and the computed values from the formula $\lambda = \frac{an^2}{n^2 - 4}$ where n is the series number and a is the value of the limit of the series *in vacuo*, derived from Rowland's values of the first three lines, viz., 3647.1369. The computed values have been corrected to air, in accordance with a table by Runge.[1]

The observed values of the lines α, β, and γ are from Rowland's table; δ and ϵ are the values found above, and are subject to the small positive correction before mentioned due to pressure-shift of the reference lines. They are not, of course, definitive values, but they

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[1] *Astronomy and Astrophysics*, **12**, 426, 1893.

TABLE IV

WAVE-LENGTHS OF HYDROGEN LINES

Designation	Observed	Computed	O.−C.
α	6563.045	6563.063	−0.018
β	4861.527	4861.516	+ .011
γ	4340.634	4340.631	+ .003
δ	4101.900	4101.893	+ .007
ε	3970.212	3970.225	− .013

show much a closer accordance with the values derived from Balmer's formula than is the case with Rowland's measures of these two lines.

SOLAR PHYSICS OBSERVATORY
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WAVE-LENGTH MEASUREMENTS FOR THE ESTABLISHMENT OF A SYSTEM OF SPECTROSCOPIC STANDARDS[1]

By C. FABRY and H. BUISSON

I. INTRODUCTION

The researches about to be described were undertaken as a result of a decision of the Congress of the International Union for Solar Research held at Oxford in 1905. In accordance with this decision, the wave-lengths of a certain number of arc lines were to be taken as standards for spectroscopic measurements. Briefly let us recall the considerations which led to this.

All spectroscopic measurements (determinations of the wave-lengths of the light corresponding to various lines of the spectrum) are carried out by interpolation, the wave-length of any line being expressed in terms of the known wave-lengths of neighboring lines. In order to make these measurements it is thus necessary to know the wave-lengths of a certain number of lines (standards, or normal lines). It is desirable that these be sufficiently numerous to render interpolation always easy.

A group of standards constitutes what may be called a system of wave-lengths. Its precision limits that of all other spectroscopic measurements. But the powerful dispersive apparatus at present

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[1] Translated from the authors' manuscript by Professor R. R. Tatnall of Northwestern University.

available (Rowland gratings or prism-trains) admits of making, by interpolation, measurements of relative wave-lengths accurate to one part in a million. Hence it is necessary that the wave-lengths of the standards shall be known with an accuracy of at least one part in a million.

From a purely spectroscopic point of view, wave-lengths appear only as ratios; we might express them in terms of an arbitrary unit. But since wave-lengths are actual lengths, it is evidently reasonable to refer them to the ordinary unit of length, the meter. The comparison of a wave-length with the meter is a metrological process, requiring special methods, and demanding the use of the material standard which represents the meter, while the comparison of two wave-lengths is a purely optical process. The establishment of a system of wave-lengths thus comprises two distinct parts: (1) comparison of a wave-length of a certain radiation with the meter; (2) measurement of the ratios of the wave-length of this radiation to those of a certain number of others which are to serve as standards in the spectrum.

The older systems of wave-lengths, such as that of Ångström, did not aim at a high degree of precision; the values were given to five figures only, that is, with an accuracy of less than one in a hundred thousand, an accuracy no doubt sufficient in view of the small dispersion of the apparatus then employed.

During the last twenty years, all spectroscopic measurements have taken Rowland's numbers as a starting-point, although other observers have, during the same period, given results of at least equal precision. The numbers given by Rowland comprise all the lines which he was able to observe in the solar spectrum (about 20,000) and a small number of metallic lines derived from arc spectra. The absolute value constituting the basis of the system was the wave-length of the D_1 line obtained by Bell in Rowland's laboratory. A certain number of lines were compared with this by the method of coincidences, and the others were determined by interpolation.

Rowland believed that the absolute values were correct to one part in one hundred thousand, and that the ratios of the wave-lengths should not contain errors exceeding one part in a million.

The absolute measurements of Michelson and Benoit, in 1893, upon cadmium lines, showed that Rowland's values were in error by about 1 in 30,000. Spectroscopists paid little attention to this result. They were interested only in the ratios of wave-lengths, and there was no reason to doubt the relative accuracy of Rowland's values. In 1901, Fabry and Perot[1] made a series of interferential measurements upon solar lines. Some thirty lines between λ 4643 and λ 6471 were compared separately with one of the lines of cadmium. Let λ be the exact wave-length thus determined, and λ_1 the value given by Rowland for the same line. If Rowland's numbers are correct in relative value, the ratio $\frac{\lambda_1}{\lambda}$ should be the same for all lines. This is not the case. The ratio varies from one line to another, and it varies in a regular manner in that part of the spectrum which was studied. For two lines which are near each other this ratio has sensibly the same value; for two distant lines the discrepancy may reach eight parts in a million. Thus, although the accidental errors in Rowland's tables are very slight, there are systematic errors which considerably affect the ratios of the wave-lengths.

These errors may be attributed to the use of gratings, which inevitably show systematic errors of ruling. Moreover, Kayser[2] has undertaken to repeat the wave-length comparisons by the coincidence method, using Rowland gratings. He has found that the results depend upon the gratings employed.

We may conclude that the grating, which is an excellent dispersive piece, is well adapted for measurements made by interpolation within a narrow interval, but is unsuitable either for absolute measurements or for the comparison of widely separated lines.

It should further be stated, in regard to the use of Rowland's standards, that they are based upon solar lines. But one nearly always employs in standard measurements, not solar light, but that of an artificial source, such as the arc or spark. Many lines of these sources correspond to dark lines of the solar spectrum, but there is no absolute identity of wave-length. It is true that Rowland has given the wave-lengths of a certain number of arc lines, yet these lines are comparatively few, and their wave-lengths are subject to uncertainty,

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[1] *Annales de Chimie et de Physique* (7), 25, 98, 1902; *Astrophysical Journal*, 15, 73 and 261, 1902.

[2] *Astrophysical Journal*, 19, 157, 1904.

because they were measured with less care than the solar lines, and with a preconceived idea that the differences between the solar lines and the arc lines ought to be zero or exceedingly small.

In conclusion, the following reasons are sufficient for the rejection of Rowland's system: the absolute values are wrong by one part in 30,000; the relative values show systematic errors amounting to nearly 1 in 100,000; and finally, the measurements are based upon the solar spectrum, while metallic spectra are usually employed for purposes of comparison.

This question was the subject of several reports presented at the first meeting of the International Union for Solar Research.[1] Most authors (Crew, Perot and Fabry, Kayser) agreed as to the necessity of establishing a new system of wave-lengths, derived from artificial sources. No decision was reached at this meeting, which was, in a sense, preliminary.

The second meeting (Oxford, 1905) took up the question anew, and arrived at the following decisions:[2]

1. The wave-length of a suitable spectroscopic line shall be taken as the primary standard of wave-length. The number which defines the wave-length of this line shall be fixed permanently and thereby define the unit in which all wave-lengths are to be measured. This unit shall differ as little as possible from 10^{-10} meter, and shall be called the Ångström.

2. Secondary standards are required at distances not greater than 50 Ångström units. These secondary standards should be referred to the primary standard by means of an interferometer method. The source of light should be obtained by means of an electric arc of from 6 to 10 amperes.

The adoption of arc lines, in preference to solar lines, to serve as standards, is justified by the following considerations: an artificial source is more convenient to use; one has it always at hand; in most cases bright lines are more serviceable than dark lines; and finally, the wave-lengths of solar lines are affected by the motions of the sun and of the earth, and perhaps also by phenomena

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[1] *Astrophysical Journal*, **20**, 301, 1904.

[2] *Transactions of the International Union for Co-operation in Solar Research*, 1, 230, 1906.

peculiar to the sun, which are not constant, and which cannot be controlled.

The maximum interval of 50 Ångströms between two consecutive lines requires the determination of about one hundred standards throughout the whole of the visible and ultra-violet spectra. This large number of standards is necessary; with spectroscopes of large dispersion only a small portion of the spectrum can be observed at one time, and this should contain several standards. The necessity is still more marked in the case of prism spectroscopes, in which the formulas of interpolation are not simple.

In 1907, a third meeting took place at Meudon. It was then possible to reach a definite decision in regard to the choice of a primary standard. The determinations of Benoit, and Fabry and Perot, in almost rigorous accordance with those of Michelson and Benoit, give for the wave-length of the red cadmium line the value $6438.4696 \times 10^{-10}$ meter in dry air at 15° C. and under normal pressure. It was decided to adopt the red cadmium line as the primary standard, and to designate its wave-length by the number 6438.4696 Ångströms. This is the definition of the Ångström; it may be considered as certain that it is equal to 10^{-10} meter with an accuracy of about one part in ten million.

Our work has for its object the determination of the secondary standards. Before deciding upon these, it was desirable that independent measurements should be made by several persons. At the time of the Meudon meeting, our investigation was the only one completed, so that no decision could then be reached.

II. SOURCES OF LIGHT

The cadmium light, which is to serve as primary standard, is produced by a Michelson tube, fed by continuous current from a battery of small accumulators having a voltage of about 1200; the current, which is of a few milliamperes, is regulated by a liquid resistance.

Instead of employing cadmium light for the direct comparisons with other radiations, we have preferred to adopt an intermediary standard, which is more convenient to use, and better situated in the spectrum, from a photographic standpoint. For this purpose we have used the Cooper-Hewitt mercury vapor lamp, which gives a very intense light. We have chosen the green line at λ 5460 for the intermediary standard. A cell containing normal potassium chromate, and one of didymium chloride absorb all other radiations; the didymium cell being unnecessary if the photographic plates used are but slightly sensitive to the yellow.

The lines which we have measured are produced by means of the electric arc, and chiefly by the iron arc. This arc was formed between two iron rods 7 mm in diameter, placed vertically, and in a holder for hand-regulation. The use of an automatic feed would have resulted in nothing but inconvenience, since the rate of consumption of the iron rods is very small. The current, which should be continuous, was usually of from 3 to 5 amperes. On increasing the current strength, the lines widen out, and the measurements become less accurate, and with some lines even impossible. The arc is extremely stable, provided the current is not too strong, nor the voltage of the source too low. This source was most commonly a distributing system at 110 volts, in which was inserted an adjustable resistance of some twenty ohms. Under these conditions, the arc was so stable that it was possible to make photographic exposures of half an hour without touching it. In exceptional cases we have made use of the same current strength under 220 volts pressure. One may thus obtain an arc, which, while very stable, is longer, so that the light emitted by different parts of the arc may be more readily separated.

In the choice of lines to be measured, one is compelled to keep within the interval of 50 Ångströms between consecutive lines. Most of the very strong lines were not measured because they were not sharp enough. All those were included which had been measured by Fabry and Perot. In certain parts of the spectrum, lines available as standards are lacking. We have measured two lines of manganese which are always present with sufficient intensity in the spectrum of the arc between ordinary iron rods. In the neighborhood of λ 5800 we have measured four nickel lines given by the arc playing between two rods of that metal; this arc being as stable as that of iron. Finally, in the extreme ultra-violet, the iron lines become, for the most part, very faint; and we have measured three silicon lines formed by the arc between carbons, such as are used for illumination. In this region, the continuous spectrum due to the carbons no longer exists; there is nothing but the light emitted by the gaseous part, and the lines of silicon are the brightest.

III. METHOD

The method employed admits of comparing each radiation with the same fundamental radiation, so that the relative measurements upon various lines are completely independent of one another. This method is the interferential one, depending on the use of silvered surfaces. Although it has already been described in detail, a brief description will be repeated here.

The interference apparatus consists of two plates of glass or of quartz, each having one silvered surface. These surfaces are put face to face, and brought into exact parallelism. They inclose between them an air-film of uniform thickness, e.

Let us suppose this apparatus illuminated by a source of monochromatic light of wave-length λ, and let us observe with a telescope focused upon infinity. To each point of the field corresponds a definite direction of the rays, and consequently a determinate angle of incidence at the air-film. For a given point, M, of the field, let the angle of incidence be i. This point M receives one ray which has traversed the apparatus, one which has suffered two reflections at the faces of the air-film, one which has suffered four reflections, and so on. The differences of path of these several rays with respect to the first ray will form an arithmetical progression whose difference is $2e \cos i$. The order of interference at the point M will be $\frac{2e \cos i}{\lambda}$.

We see from this that the interference phenomenon takes the form of rings with their centers at that point of the field which corresponds to normal incidence upon the silvered surfaces, i. e., the point for which $i = 0$. The bright rings are fine lines, separated by wide dark intervals, and this characteristic becomes more marked as the reflecting power of the surfaces increases. Each ring is characterized by an integral order of interference, which diminishes by unity from one ring to the next, from the center outward. The angle of incidence has the same value for all the points of any one ring; we shall call it the angular radius of the ring. Twice this quantity is the angular diameter, denoted by a.

Let P be the integral number designating the order of the ring, while a is the angular diameter. The order of interference at the center, where $i=0$, will be represented by p. Thus we have $p=\frac{2e}{\lambda}$, and consequently $P=p\cos\frac{a}{2}$. The angle being small, this gives

$$p=P+P\frac{a^2}{8}.$$

We shall see later how to determine the integer P; the measurement of a will then permit us to calculate p. For this measurement we use the first or second ring from the center. Let λ' be the wave-length of another radiation. Upon repeating the above determinations, we shall have

$$p'=\frac{2e}{\lambda'}=P'+P'\frac{a'^2}{8},$$

whence,

$$\lambda=\lambda'\frac{p'}{p}.$$

The wave-length λ being that which is to be measured, and λ' that which serves as the fundamental standard, the problem is solved.

We have supposed the integers P and P' to be known. For P' we use the coincidence method described by Fabry and Perot, starting with an approximate determination of the thickness, and employing the radiations of mercury and cadmium. Having, in addition, measured a', we may compute p'.

One has always an approximate value λ_1 of the wave-length λ. The equation $p\lambda=p'\lambda'$ then gives a means of calculating an approximate value p_1 of the order of interference p. If the error of the number λ_1 is not too great, the order of interference of the central ring is the integer next smaller than p_1. Admitting this result, and having measured the diameter a of one of the rings, one obtains the order of interference at the center p. The fractional part of p as measured should not differ from the calculated fractional part of p_1 by more than 0.1 or 0.2, if there is to be no uncertainty as to the integral part.

In a word, the whole matter reduces to the measurement of the angular diameters of the rings produced by the radiations to be compared.

The ray λ being, in our experiments, a ray of the iron arc, it is necessary, in order to observe its interference figures, to separate it from the other rays emitted by the same source. In the experiments of Perot and Fabry, which were made visually, this separation was secured by projecting a spectrum of the source, and isolating by means of a slit, the line to be measured. The light which passed through then fell upon the interference apparatus, and produced the rings. The actual measurements were made entirely by the photographic method. The old method would, under these conditions, have been difficult to apply. We were led to adopt an arrangement such that there would appear on each plate the interference figures produced by a large number of lines. To secure this result it was only necessary to place the interference apparatus in front of the dispersive piece.

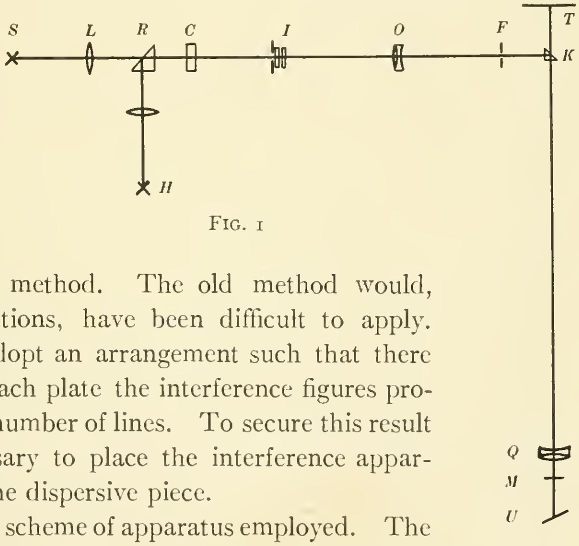

Fig. 1

Fig. 1 shows the scheme of apparatus employed. The light emitted by the arc S passes through a converging lens L, and the interference apparatus I. If necessary, an absorption cell is interposed at C, in order to remove portions of the spectrum which are not wanted. The objective O projects the interference rings upon its focal plane F. According to this plan, each radiation gives its own system of rings, all of which have their centers at the same point. All that remains is then to separate the various radiations. The slit of a spectroscope is placed in the plane F, and so as to coincide with a diameter of the system of rings. The spectroscopic apparatus, provided with a plane grating (it is necessary to avoid astigmatism), thus yields as many images of the slit as there are separate wave-lengths in the incident light. Each of these images presents the result which would be obtained if the source emitted the corresponding radiation only, upon the portion of the plane *F* which is occupied by the aperture of the slit. The latter should be of such a width as to prevent the image corresponding to the radiation to be measured from encroaching upon the adjacent images. With spectra having few lines one may employ a very wide slit, thus obtaining complete rings; if the spectrum is very rich in lines the slit must be narrow, and the image then reduces to the bright points in which the slit intersects the rings. Fig. 2 presents both of these cases.

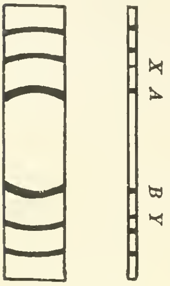

Fig. 2

The arrangement of the dispersive apparatus varies according to circumstances, as explained in subhead IV. That represented in the diagram, Fig. 1, is the auto-collimating system. The image is thrown upon the photographic plate *T*. It is possible to measure on the same plate the rings due to all the rays present in the photographic portion of the spectrum.

In addition, it is necessary to obtain the rings produced by a comparison line. We have employed for this purpose the green mercury line emitted by the Cooper-Hewitt lamp, placed at *H*. A totally reflecting prism *R*, introduced into the incident beam, directs the mercury light, instead of that from the arc, into the interference apparatus. The spectroscope becomes useless for light, which by reason of having been passed through suitable absorption cells may be regarded as monochromatic. A plane mirror, interposed at *M*, in front of the grating, throws upon the plate *T* a real image of the rings of the mercury line.

It is necessary to determine the angular diameters of the rings. For this purpose, we measure, upon the plate, the diameter, *AB*, of one of these, whence we may deduce the angular diameter if we know the scale of the image, that is, the number of millimeters corresponding to a given angle. To accomplish this, there are placed across the slit two metallic landmarks, which project upon each image two straight lines, *XY* (Fig. 2). When *AB* is measured there is also made a measurement of the distance $XY=r$, of the images of these reference wires. The angle corresponding to the distance *XY* has been previously determined, once for all. Thus we have all the elements necessary for the computation.

IV. DESCRIPTION OF APPARATUS

The optical arrangement which is about to be described requires modification according to the portion of the spectrum to be studied. For the ultra-violet beyond λ 3600 all glass must be eliminated. We shall describe in succession the different pieces of apparatus composing the outfit.

Interferential apparatus.—This consists of two transparent plates, each presenting a plane silvered face. These are kept exactly parallel to each other, and at an invariable distance apart. The apparatus which has been previously described under the name of standard of thickness,[1] was constructed by Jobin. For wave-lengths greater than 3600 the plates are of glass. They were silvered either by the chemical method or by cathode projection, using the apparatus of our colleague Houllevigue.[2] This last method yields silver films of remarkable regularity, and of very high reflecting power, in spite of considerable transparency. Unfortunately, the properties of the silver thus obtained are not always the same, and it is difficult to produce a film which shall meet given conditions.

For wave-lengths below 3600 quartz plates are used. The reflecting power of chemically deposited silver becomes very small in the neighborhood of λ 3300, and the interference figures disappear. Some of the silverings obtained by cathode projection behave in the same way; with others, the reflecting power does not fall off so rapidly, so that we have been able to use them for very short wave-lengths; however, their reflecting power becomes feeble toward the end of the ultra-violet spectrum, and in this region we have been obliged to make use of quartz plates nickeled by cathode projection.

From the standpoint of precision of measurement, it is advantageous to employ interferences having a large difference of path; but there is a limit to this in the fact that the lines are not infinitely narrow, so that the fringes lose their sharpness when the thickness of the air-film becomes too great. The orders of interference used

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[1] See footnote 1, p. 171.

[2] *Journal de Physique* (4), 4, 396, 1905.

have varied from 14,000 to 27,000. For wave-lengths greater than 3600 the thickness of the air-film was 5 mm, while for those less than 3600 it was 2.5 mm.

A diaphragm was used in the interference apparatus in such a way as to employ a field only 8 mm in diameter, this being kept the same for all the rays compared. Thanks to this precaution a slight lack of parallelism of the surfaces was without influence.

The apparatus is carried upon a support, constructed by Jobin, which admits of various motions: a double translation allows it to be brought into the beam of light, and it may then be oriented by two rotations in such a way as to center the rings on the slit.

Dispersive apparatus.—Since it is essential to avoid astigmatism, the use of a concave grating is out of the question. We have made use of plane gratings with an arrangement for auto-collimation. Light which has passed the slit is reflected by the totally reflecting prism *K* (Fig. 1), and falls upon the objective *Q*, of one meter focal length, which is moved back and forth by a rack and pinion, its position being determined by means of a scale of millimeters engraved upon the sliding tube. The plane grating *U* is a Rowland grating having a ruled surface of 80 by 50 mm and ruled with 568 lines to the millimeter. It is carried upon a divided circle, by means of which it may easily be placed in a given position. The diffracted light re-enters the objective, passes beneath the totally reflecting prism, and forms the spectrum upon the photographic plate *T*, of dimensions 9 by 12 cm. This is placed in a metallic holder arranged to slide vertically, in order that several exposures may be made upon the same plate. The distance from the plate-holder to the objective may be changed by a focusing rack; and finally the plate may be set at any given angle with the axis of the objective by rotating it about the vertical line through its center. The whole is supported on a very solid cast framework made by Jobin.

When one wishes to photograph a definite portion of the spectrum, it is essential that one be able, rapidly and without hesitation, to bring each piece—grating, objective, and plate—into the proper position. To this end the following quantities have been determined in advance, and graphically represented as functions of the wave-length: (1) the inclination of the grating, which is easily calculated,

(2) the focusing position of the objective, which is experimentally studied, (3) the inclination to be given the plate in order that the spectrum shall be sharply defined through the greatest possible range, this inclination being readily deducible from the above-mentioned graph and from a study of the curvature of the field. As to the most favorable position of the plate with respect to the luminous ray, this remains invariable, and has been determined once for all.

In the case of wave-lengths greater than 3600, the objective, which is of glass, is achromatic. Its dispersion is very slight, and consequently the inclinations of the plate are small.

For the ultra-violet, the totally reflecting prism K and the objective Q are of quartz. We no longer have achromatism, and the changes of focus are considerable, as are also the inclinations of the plate.

The plane grating which was employed in the visible spectrum showed an unexpected peculiarity. Its spectra of different orders and on both sides ceased abruptly at about λ 3500. Kayser and Runge have observed a grating which exhibited the same anomaly.[1] It does not seem possible to attribute this to the form of the grooves; it is perhaps due to the optical properties of the metal on which the grating is ruled.

The auto-collimating arrangement, while exceedingly convenient, has the slight disadvantage that light reflected by the objective falls upon the plate, and may produce some fog. This is not troublesome except in the case of long exposures. For red radiations, of course, the exposures are long, but the more actinic rays may be removed by an absorption cell, so that the fog need not be feared. This, however, is not the case in the extreme ultra-violet. Here we have been forced to abandon the auto-collimating arrangement, and make use of an apparatus with separate collimator and camera (Fig. 3). The positions of collimator and grating remain unchanged, but the diffracted light falls upon a second objective of quartz, which forms the spectra on the plate T'. The camera is fixed, and the spectra are shifted by turning the grating. Focus is secured by displacing the objective Q and also the plate, while the objective Q' remains fixed.

For the most part, we have used the third-order spectrum. The

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[1] *Abhandlungen der K. Akademie der Wissenschaften zu Berlin*, 1888.

scale is then 0.18 mm per Ångström. The second-order spectrum has been used in the red, where it is very bright. It has also been used in the extreme ultra-violet, on account of the overlapping of the spectra.

In order to photograph the interference figures of the green mercury line, there is interposed in front of the grating a plane mirror *M*, carried on a support having three clamp-screws which fit into three sockets, thus permitting it to be replaced quickly in position.

Objective of the rings.—We thus designate the lens *O*, which projects the rings upon the slit. For the spectral region studied, the focal plane of this lens should contain the slit of the spectroscope.

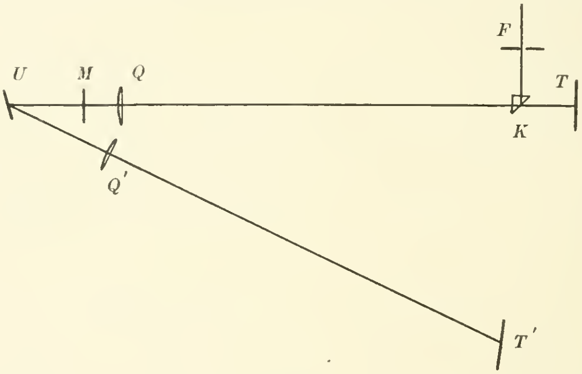

Fig. 3

It is mounted in a graduated sliding tube, and its position may be changed by means of a rack and pinion. It is an achromatic glass lens, replaced in the ultra-violet by a lens of quartz and spar. The focal length of each is about 26 cm. The dispersion of each of these lenses has been studied, and curves plotted, showing the position of the objective for each region of the spectrum.

In each case it is necessary to know the angular distance which corresponds to the distance apart of the standard landmarks placed upon the slit. This angle is defined as follows: suppose the slit to be illuminated from behind; an observer viewing it through the objective of the rings sees it at infinity, together with the marks which it carries. The angular distance of the marks thus viewed is the angle in question. This has been directly determined for the green mercury line, by using a telescope focused at infinity, and furnished with a micrometer eyepiece which has been previously calibrated in terms of angle by means of a divided circle. The angle θ for any radiation whatever, λ, is derived from the angle θ', measured in the manner just described for the green ray, by means of the formula $\theta = \theta' \frac{f'}{f}$, f and f' being the focal distances determined as already explained.

Absorption cells.—In many cases, it is desirable to eliminate certain troublesome rays. For this we employ cells containing liquids, placed at C (Fig. 1). In order to photograph the fringes in the green light of mercury, we interpose a solution of normal chromate of potassium, which eliminates the violet and ultra-violet rays. The plates which we use are not affected by the yellow rays.

When the grating is used, it is necessary to prevent the overlapping of spectra. The chromate cell suppresses all radiations of wave-length less than about 5000. An acid solution of sulphate of quinine absorbs radiations shorter than 4200. On the other hand, it may be necessary in the ultra-violet to eliminate rays of greater wave-length than those which are being studied. This service is rendered by a quartz cell, filled with a solution of nitrosodimethylaniline, as pointed out by Wood.[1] When no absorption cell is required, a cell filled with water is introduced, to diminish the heating of the interference apparatus.

Photographic plates.—One item of great importance is the reduction of the length of exposure. For all the negatives which contain no lines of wave-length less than λ 4800 (the region of sensitiveness of non-orthochromatic plates), we have used the Σ plates of Lumière. In the green region, and for the green mercury line, we have employed Smith plates. In the yellow and red we have made use either of Lumière Orthochromatic B plates, or of Cramer Trichromatic. Not until near the end of our research did we try the excellent plates of Wratten and Wainwright, the use of which would have rendered us great service, had we known of them earlier.

V. METHOD OF PROCEDURE

Mounting and adjustment.—The spectroscope, which is the heaviest part of the outfit, remains immovable, and the adjustment

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[1] *Astrophysical Journal*, **17**, 133, 1903.

is accomplished by displacing other portions of the apparatus. The sources of light, iron arc, and Hewitt lamp, with its total reflection prism, are first set up. The objective of the rings is centered upon the beam of light. The interference apparatus requires careful mounting and adjustment. Its adjustment consists in securing parallelism between the silvered surfaces. This adjustment is made by turning the clamp screws by which the glass plates are attached to the metal surfaces, and is verified by viewing with the naked eye the rings produced by the mercury light; if the eye be displaced in all directions, the diameter of these rings must remain invariable. The change in thickness of the air-film, which occurs either upon readjustment or as a result of expansion, is extremely small, and does not cause a variation in the order of interference of more than one or two units. Observation of the coincidences of the green and violet rings of mercury fixes, by simple inspection, the order of interference of the central ring.

Having completed this adjustment, the next step is to place in front of the interference apparatus the diaphragm which limits the portion of it which is made use of. The whole is then centered on the beam of light. Its distance from the objective of the rings is such that this objective projects, through the slit, and upon the grating, an image of the opening in the diaphragm. By this arrangement the interference apparatus and the grating are employed in the same manner for all the points of the image and for all radiations.

The interference apparatus should be so oriented that the center of the rings is projected on the middle of the slit.[1] In order to control this, one observes, by means of an eyepiece placed in the position of the photographic plate, the image produced by the green mercury ray.

The slit-width varies, according as the lines are more or less crowded, from 0.15 to 0.30 mm.

The concentration lens, *L*, projects an image of the arc upon the diaphragm of the interference apparatus. This image is so large

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[1] This condition is not essential to obtaining correct measurements; it is sufficient that the center of the rings, for both mercury and iron, shall fall at the same distance from the slit. It is, however, desirable, on account of the sharpness of the points, that the slit cut the rings normally, and therefore that it coincide with their diameter.

that the light from the ends of the iron rods can be eliminated. In the case of the ultra-violet this lens is of quartz, so that in adjusting it to its proper position it is necessary to take account of its lack of achromatism.

Making the negative.—The elements of a measurement include the photographing of the interference figures produced by the green mercury ray, and of those of the rays from the iron arc. To get rid of the effect of temperature changes, it is necessary to expose twice upon mercury, once before and again after the exposure corresponding to iron. These three exposures must be made without touching any part whatever of the interference apparatus or the slit. Upon the negatives thus obtained, the images of the standard marks on the slit are not always easily visible if they chance to fall between two bright rings. Consequently, it is advisable to make an exposure upon both the iron and mercury under the same conditions as before except that the interference apparatus has been removed.

The following is then the series of operations carried out:

1. Exposure on the mercury rings. Total reflection prism *R* in place, as well as the mirror *M*. The objective of the rings and that of the spectroscope focused for λ 5460. Chromate cell. Photographic plate normal to the pencil of rays.

2. Exposure on the rings of iron. Prism and mirror removed. Objectives focused for the region to be photographed. Plate inclined at the proper angle. Suitable absorption cell.

3. Exposure made on the mercury rings, exactly as before. The interference apparatus is now removed.

4. Exposure on the standard marks, with mercury light, as in operations 1 and 3.

5. Exposure on the standard marks, with light from iron, as in operation 2.

6. It is well to have on the same plate a spectrum of iron made with a narrow slit. Exposure as in operation 5, after having diminished the slit-width. During the exposure on the rings of iron, the temperature and pressure of the surrounding air are noted. According to circumstances, the six exposures are made upon the same plate or upon two different plates, one for iron and the other for mercury.

The time of exposure varies greatly with the thickness of the silver films and the region of the spectrum. For the mercury rings it is a few seconds: for those of iron it has varied from one second to thirty minutes.

VI. MEASUREMENTS

The measurements consist in the determinations of the diameters of the rings, or more exactly, in the measurement of the distances apart, *AB* (Fig. 2), of the black points on the negative which represent the intersections of the bright rings with the slit. In addition, one must determine the distance apart of the images of the reference marks. These distances do not exceed ten millimeters, and under favorable circumstances the precision of the measurements reaches a hundredth of a millimeter. We have employed a longitudinal comparator of very simple pattern.

The negative to be measured is placed vertically in a holder upon the carriage of a dividing engine. It is illuminated by transmitted light, and viewed with a micrometer telescope. Upon the same carriage is mounted a slip of glass graduated in tenths of a millimeter, and this is viewed through a micrometer microscope. One observer has his eye at the telescope, and turns the screw of the dividing engine, while the other takes readings at the microscope and records the readings. Each measurement is made twice, the carriage being displaced first in one direction, then in the other.

These measurements give, for each iron line, and for the mercury line, the distance of the standard marks, the diameter of the first ring, and if possible that of the second. Moreover, the angle corresponding to the distance between the standard marks is known (see above). For each radiation the order of interference at the center must be calculated.

Let us consider first the mercury ray. Let r' be the distance between the standard marks, θ' the corresponding angle, expressed in radians, and δ' the diameter of that one of the measured rings the number of whose order, P', is known. The angular diameter of this ring is $a' = \frac{\delta'}{r'}\theta'$. The order of interference at the center is then

$$p' = P' + \frac{P'a'^2}{8} = P' + \frac{P'}{8}\left(\frac{\delta'\theta'}{r'}\right)^2.$$

If we measure the diameters of two rings, we have two values of

p' which ought to be identical: in general they agree to within a few thousandths.

The mean is taken of the results obtained by the two exposures on the mercury ray. By reason of the presence of the observers and of the light sources, the temperature rises somewhat between the two exposures, so that the second of these gives for p' a value a few thousandths higher.

Consider now a ray of iron. Let λ be its wave-length, which is unknown. We know the values of r, δ, θ corresponding to the rings of this ray. The ring whose diameter is δ has for the number of its order the integer P which is not yet known. We proceed to determine this by means of the known approximate value λ_1 of the wave-length λ. This value is taken from Rowland's tables, and is multiplied by 0.999967, the mean ratio between the true wave-lengths and those of Rowland.

The equation $p\lambda=p'\lambda'$, upon substituting for λ its approximate value λ_1, gives an approximate value p_1 of the order of interference, p. If the approximation is sufficiently close, no error is introduced in the integral part. The number of the first ring is the integer next smaller than p_1, and this determines the numbers of all the rings, and in particular the number P of the ring measured. We then calculate the order of interference at the center by the formula

$$p=P+\frac{P}{8}\left(\frac{\delta\theta}{r}\right)^2.$$

An error of a unit in the approximate value need cause no alarm: for example, the order of interference being say 20,000, it would be necessary for the approximate value λ_1 to be in error by 1/20,000, in order to cause a like error. As a matter of fact, the error is much less; the fractional part of p, the order of interference as measured, differs from that of the approximate value p_1 by a quantity considerably less than unity. In general the difference does not exceed 0.1.

The orders of interference are thus determined with an uncertainty of less than 0.01. As they are all in the neighborhood of 20,000, the relative error is less than 1/2,000,000. In the most unfavorable cases, the uncertainty in the value of λ does not reach one part in a million.

For a given negative, the order of interference, p', relative to mercury, is a constant. We calculate, once for all, the product $p'\lambda'$ which represents twice the thickness of the interference apparatus. This thickness is thus determined with an accuracy of the order of $0.002\ \mu$.

VII. CORRECTIONS

1. *Correction for phase.*—We have proceeded on the assumption that the optical thickness of the air-film is the same for all radiations. This is not rigorously true, on account of the change of phase at reflection from silver, which varies very slightly with wave-length. Everything takes place just as if each radiation suffered, without change of phase, reflection at a certain plane, which may be called the optical surface of the silvered glass, the position of this plane changing slightly from one ray to another.

In order to escape the influence of this variation, it is sufficient to make, at the start, two observations with the same silverings, using two different thicknesses of air. This is, as we shall see, what we have done, but one of the thicknesses used is so small that the exact knowledge of the wave-lengths is useless for calculating the corresponding results, and the observations made with the small thickness solve in themselves the problem of change of phase.

Let λ' and λ be the wave-lengths of the green mercury line, and of any other radiation, respectively. The corresponding thicknesses of the air-film have the very slightly different values e' and e. The question resolves itself into the determination of the difference $e-e'$, as we proceed to show.

The corresponding orders of interference are $p'=\frac{2e'}{\lambda'}$ and $p=\frac{2e}{\lambda}$, whence,

$$\lambda=\frac{e}{e'}\times\frac{p'}{p}\times\lambda' .$$

Instead of making the calculation in this manner, we have reasoned as if the thickness had been the same, while we have given to λ the very slightly inexact value $\frac{p'}{p}\lambda'$. We may correct this value by adding to it the correction

$$\eta=\frac{e}{e'}\times\frac{p'}{p}\times\lambda'-\frac{p'}{p}\lambda'=\frac{2(e-e')}{p} .$$

The probem will be solved if for each radiation we know the difference $\epsilon=2(e-e')$ of the doubled optical thicknesses corresponding to the two radiations λ and λ'. This difference is evidently independent of the thickness itself; λ' being fixed, it is a simple function of λ, which may be determined, for given surfaces, once for all.

It is sufficient for this purpose to make use of interferences of a low order, using rays whose wave-length is quite closely known. With the same surfaces, let us form an air-film only a few microns in thickness, in such a way that the orders of interference, q and q', are not greater than a score or so. These quantities being once known, we have $2e=q\lambda$ and $2e'=q'\lambda'$, and since q and q' are very small, these equations give e and e' with very great absolute precision, even though the wave-lengths are not very exactly known. We may then calculate the difference $\epsilon=2(e-e')$. Having repeated this process for various radiations, one may plot a curve giving ϵ as a function of λ. Since, in general, this function does not vary rapidly it is sufficient to make the measurements for a few radiations distributed throughout the spectrum.

Having obtained this curve, it is easy to plot a correction curve applicable to these silverings when employed with a given air-thickness. We have

$$\eta=\frac{\epsilon}{p}=\frac{\epsilon}{2e}\lambda\,.$$

The problem reduces itself to the observation, for certain radiations, of the orders of interference, while working with a film of very small thickness. We have used thicknesses of the order of 8 μ. We have made use of the fringes of thin plates, as being more convenient, in this case, than the rings at infinity. They are produced by parallel light, and exhibit the lines of equal thickness of the air-film.

Upon one of the silvered surfaces there have been traced with a fine point several standard marks arranged along a straight line, and each consisting of two intersecting straight lines. The two silvered surfaces are then superposed, being held apart by three strips of thin tinfoil placed around their edges. The whole is then tightly held in a screw clamp. Viewing this by transmitted monochromatic light, one sees rectilinear fringes, whose distance apart and orientation may be varied by turning the screws of the clamp. They are thus brought into perpendicularity to the line of standards. We first examine them by mercury light. To each point of the film, and in particular to each standard, corresponds, with the green light, a definite order of interference. The numbers of the green fringes are easily obtained by examining their coincidences with the yellow and violet fringes. The order of interference corresponding to any standard is deduced from a measurement of the distances of this standard from the neighboring fringes. In Fig. 4 the fringes are indicated by black lines, and their numbers are shown. For the standard R the value of the order of interference is $35+\frac{RA}{AB}$. Let q' be the order of interference thus found. This process is repeated for any other radiation, λ; and the order of interference q determined in the same way: its fractional part by interpolation, and its integral part by calculating in the first place the approximate value of q, namely, $\frac{q'\lambda'}{\lambda}$. One may then calculate the values of the double optical thicknesses $2e=q\lambda$ and $2e'=q'\lambda'$ and consequently $\epsilon=2e-2e'$.

We have employed most frequently the radiations of mercury (the Hewitt lamp for the visible spectrum, the quartz lamp of Heraeus for the ultra-violet). In certain cases we have used the rays of the iron arc. Nearly all the measurements have been made photographically. An image of the thin film is projected upon the slit of the spectroscope in such a way that the image of the standards traced on the film shall fall on the slit. The measurement of the negatives is made with the help of the longitudinal comparator previously described. Settings are made on the several fringes and on the standards, and from these are deduced the order of interference of each. These quantities are thus determined with an uncertainty of less than 0.01, that is to say, of the same order as is attained in the measurement of the rings at infinity.

In this computation the wave-lengths are regarded as known, but it is not necessary to know them with great precision. Supposing that we have fringes of order 40, q is determined to 1/4000, very nearly. If λ is in error by 0.1 Ångström, this will cause in $2e$ an error ten times less than that which results from the uncertainty of q, and therefore negligible.

These experiments have been repeated for each of the silverings which we have used. The properties of silverings chemically produced seem to be always identical among themselves, and depend only on the thickness. For these we have obtained results in the same sense and of the same order of magnitude as those indicated by Perot and Fabry. As one approaches wave-length 3300, not only does the reflecting power rapidly diminish, but the change of phase also undergoes a rapid variation. On the contrary, the silverings obtained by cathode projection do not all behave alike as regards the size, or even the sense, of the difference ϵ.

2. *Correction for the temperature and pressure of the air.*—It has been decided that all wave-lengths shall be expressed in terms of their values in dry air at 15°, and under normal pressure, and the number adopted for the wave-length of the red ray of cadmium was obtained under these conditions. Variations in the condition of the air cause the wave-lengths to change in absolute value by quite considerable amounts. On the other hand, the ratios of wave-lengths vary by very small quantities only, for the effect is due entirely to the dispersion of the air. If the index of refraction of the air were constant through the spectrum, all wave-lengths would vary in the same ratio. If this were the case, our measurements would give the wave-lengths directly as under normal conditions, whatever might be the state of the atmosphere at the time of making the measurements, since the value adopted for the fundamental wave-length and introduced into the calculations is that corresponding to these normal conditions. However, the dispersion of the air is not zero; hence a correction must be made, although very slight, depending upon the atmospheric conditions at the time of obtaining the negative. By "actual conditions" we shall designate those which exist at this moment, and by "normal conditions" those corresponding to 15° and normal pressure.

Let M be the specific mass of the air under actual conditions, defined by the temperature t and the pressure H; λ the wave-length of a ray under actual conditions, n the corresponding index of the air under the same conditions; λ' and n' the analogous quantities for the green ray of mercury. The same letters with subscript zero will represent the same quantities under normal conditions. The quantity which we wish to find is $\lambda_\circ$. We have measured the orders of interference p and p' under actual conditions, and hence obtained $p\lambda = p'\lambda'$. The calculation was conducted in the following manner: we have computed the quantity $\frac{p'\lambda'_\circ}{p}$, which would be the normal wave-length if the air were not dispersive, and to this has been applied a correction.

This correction, which is the difference between the exact value and that which is to be computed, has the value

$$\gamma = \lambda_\circ - \frac{p'\lambda'_\circ}{p} = \lambda_\circ\left(1 - \frac{p'}{p} \times \frac{\lambda'_\circ}{\lambda_\circ}\right) = \lambda_\circ\left(1 - \frac{\lambda\lambda'_\circ}{\lambda'\lambda_\circ}\right),$$

but

$$\frac{\lambda}{\lambda_\circ} = \frac{n_\circ}{n} \text{ and } \frac{\lambda'}{\lambda'_\circ} = \frac{n'_\circ}{n'},$$

and hence

$$\gamma = \lambda_\circ\left(1 - \frac{n_\circ\, n'}{n'_\circ\, n}\right) = \lambda_\circ \frac{n'_\circ\, n - n_\circ\, n'}{n'_\circ\, n},$$

in which the denominator $n'_\circ n$ may be replaced by unity. We have also,

$$\frac{n-1}{M} = \frac{n_\circ - 1}{M_\circ} \text{ and } \frac{n'-1}{M} = \frac{n'_\circ - 1}{M_\circ}.$$

Solving these equations for n and n', and introducing these into the expression for γ, this becomes

$$\gamma = \lambda_\circ(n_\circ - n'_\circ)\frac{M - M_\circ}{M_\circ}.$$

The factor $\frac{M - M_\circ}{M_\circ}$, which is easy to calculate as a function of the temperature and pressure, is constant for all the rays of any one negative. Moreover, the quantity $\lambda_\circ(n_\circ - n'_\circ)$ has been calculated as a function of the wave-length, and plotted in a curve.

These corrections do not reach a value of any consequence, except in the extreme ultra-violet; the largest we have met with is about 0.007 Ångström.

3. *Measurement of the green mercury ray.*—The green mercury line is accompanied by numerous satellites; hence it is unsuitable for a primary standard. We have used it merely as an intermediary,

on account of its brightness and the convenience attending its employment. Its wave-length has been compared with those of the cadmium lines, and this for every thickness of air-film employed, and for each of the silverings. In this way has been eliminated all error due to the influence of the satellites. This comparison was made visually, and without dispersive apparatus. One may transmit through the interference apparatus light from either source at will, suitable absorption-cells being interposed. The rings are observed by means of a telescope focused at infinity, and provided with a micrometer which has been calibrated for angular readings.

VIII. RESULTS

The number of negatives used in these measurements was 43, of which 22 were obtained with glass apparatus, and 21 with quartz. Each plate contains, usually, an interval of 600 Ångströms, but in the regions in which the defects of achromatism make themselves chiefly felt, the whole extent of the plate is not available. In the most favorable cases, we have measured fifteen or twenty lines on the same plate. The same part of the spectrum always occurs on several plates.

The total number of measurements carried out has been 405, involving 115 different lines.

We give here a complete example of a measurement.

Conditions under Which the Negative Was Made

Negative 56. March 17, 1906. Smith plate. Temperature 17°.6. Pressure 765.

Interference apparatus of 5 mm thickness. Glass plates silvered by cathode projection.

Slit-width 0.3 mm.

For the mercury rings, time of exposure 30 seconds.

For the iron rings, time of exposure 10 seconds, wave-length at middle of plate 3800. Inclination of the plate 12°. Intensity of arc current 3 amperes.

Measurement of the Mercury Rings

	1st Ring $P'=18336$	2d Ring $P'=18335$	Distance of Standards
Exposure 1	$\delta'=2.675$	$\delta'=6.11$	$r'=8.12$
Exposure 2	$\delta'=2.735$	$\delta'=6.115$	$r'=8.12$

All these lengths are expressed in millimeters.

Angular distance of the standards placed upon the slit, $\theta' = 0.03091$.

The order of interference is then calculated from the formula

$$p' = P' + \frac{P'}{8}\left(\frac{\theta'\delta'}{r'}\right)^2,$$

which gives the following values:

	Calculated from 1st Ring	Calculated from 2d Ring	Mean
Exposure 1	18336.238	18336.242	18336.240
Exposure 2	.248	.244	.246

Final mean, $p' = 18336.243$

The wave-length of the green ray, obtained with these silverings and this interference apparatus, is $\lambda' = 5460.741$.

Consequently $p'\lambda' = 10012.947\ \mu$.

Measurement of the Iron Rings

Wave length given by Rowland.................... 3977.891

The same corrected.............................. $\lambda_1 = 3977.76$

Approximate value of the order of interference ...... $p_1 = \dfrac{p'\lambda'}{\lambda_1} = 25172.32$

Angle between standards.......................... $\theta = 0.03040$ radian

Distance between standards...... .... $r = 8.09$ mm

	1st Ring	2d Ring
Diameter of rings, δ	3.02	5.625
Number of order, P	25172	25171
Computed order of interference	25172.406	25172.407

Mean, p 25172.406

Rough value of wave-length, $\dfrac{p'\lambda'}{p}$ 3977.7473

Correction for air 0

Correction for phase .... -0.0019

Corrected wave-length.......................... 3977.7454

All the lines have been measured several times; some of them with the surfaces of the interference apparatus covered with different metals (silver deposited by cathode projection, chemically deposited silver, and nickel). The results, before being corrected for phase, are extremely discordant; after these corrections are applied they become very concordant. As an example of this, we may give the numbers obtained with a line situated in the region of the spectrum in which the properties of chemically deposited silver vary rapidly, and where, consequently, the corresponding phase corrections are considerable. In the following table, we give the numbers of the negatives, the nature of the metallic surface, the value of the wave-length corrected for the effect of air, but not for phase-change, the value of this correction, and finally the corrected wave-length λ. The integral part of the wave-length, 3399, is not repeated in the table.

	Silver Deposited from Cathode		Silver Deposited Chemically				Nickel
Negative	134	136	175	177	194	195	254
λ uncorrected	3399·3440	·3440	·3140	·3145	·3128	·3134	·3280
Correction for phase	−.0064	−64	+233	+233	+233	+233	+91
λ corrected	3399·3376	·3376	·3373	·3378	·3361	·3367	·3371
Mean			3399·3372				

The following table gives the definitive result of the measurements:

2373·737
2413.310
Si 2435·159
Si 2506.904
Si 2528.516
2562.541
2588.016
2628.296
2679.065
2714.419
2739·550
2778.225
2813.290
2851.800
2874.176
2912.157
2941.347
2987.293
3030.152
3075·725
3125.661
3175·447
3225·790
3271.003
3323·739
3370·789
3399·337
3445·155
3485·344
3513·820
3556.879
3606.681
3640.391
3677.628
3724·379
3753·615
3805·346
3843·261
3865·526
3906.481
3935.818
3977·745
4021.872
4076.641
4118.552
4134.685
4147.677
4191.441
4233.615
4282.407
4315·089
4352·741
4375·935
4427·314
4466.554
4494·572
4531·155
4547·854
4592.658
4602.944
4647·437
4678.855
4707.287
4736.785
Mn 4754·046
4789.657
Mn 4823.521
4859·756
4878.226
4903·324
4919.006
4966.104
5001.880
5012.072
5049.827
5083·343
5110.415
5127·364
5167·492
5192.362
5232.958
5266.568
5302.316
5324·196
5371·498
5405·780
5434·530
5455·616
5497·521
5506·783
5535·418
5569·632
5586.770
5615.658
5658.835
5709·396
Ni 5760.843
5763·013
Ni 5805.211
Ni 5857·760
Ni 5892.882
5934·683
5952·739
6003.039
6027.059
6065·493
6137·700
6191.569
6230.732
6265.147
6318.029
6335·343
6393.612
6430.859
6494·994

Comparison with previous results.—Among the lines which we have measured are the fourteen lines visually measured by Fabry and Perot in 1901. These older measurements were founded upon the value 6438.4722 for the red cadmium line, as given by Michelson and Benoit. Upon reducing these to the same unit as the actual measurements, they become very concordant with these latter. The differences amount to but a few thousandths of an Ångström, sometimes in one sense, sometimes in the other. One difference only is as great as 0.007. The mean of the differences, taken with their proper signs, is only 0.0006; there is therefore no systematic variation between the two series of determinations. The mean of the differences taken without regard to sign is 0.004, which is less than one-millionth in relative value.

A comparison of our numbers with those of Rowland would have no definite significance, because the one set is based on the spectrum of iron, while the other is founded on the solar spectrum, and there is no identity between the two sorts of lines. If the ratios of Rowland's numbers to ours be taken, they are always found to vary systematically through the spectrum in such a way as to confirm the results announced by Perot and Fabry.

A REDETERMINATION OF THE WAVE-LENGTHS OF STANDARD IRON LINES

By A. H. PFUND

As it has been shown by Fabry and Perot[1] and by Kayser[2] that the grating method is not well adapted for the accurate determination of secondary standards of wave-length, it has been decided by the International Union for Co-operation in Solar Research that the problem be attacked by means of the interference method of Fabry and Perot. In order to establish these new standards with definiteness, determinations have been carried out by the same method and on the same iron lines by Fabry and Buisson[3] at Marseilles, by Eversheim[4] at the Physical Institute of the Universität Bonn, and by the writer at the Physical Laboratory of the Johns Hopkins University.

GENERAL DESCRIPTION OF APPARATUS

As the theory of the Fabry and Perot interferometer and the formulae used in the calculation of wave-lengths have been fully given by Fabry and Perot,[5] Lord Rayleigh,[6] Eversheim,[7] and Zeeman,[8] it would be unnecessary repetition to discuss these matters once more. I shall therefore limit myself to a description of the apparatus and a discussion of applications of the formulae. The apparatus may be described briefly as follows: A mirror at M (Fig. 1), consisting of two thin pieces of plane glass, was so adjusted as to give the same direction to the two beams of light coming, respectively, from the cadmium lamp (C) and the iron arc (I). After having been

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[1] Fabry and Perot, *Astrophysical Journal*, **15**, 261, 1902.

[2] Kayser, *ibid.*, **19**, 157, 1904.

[3] Fabry and Buisson, *Comptes Rendus*, **143**, 165, 1906, and **144**, 1155, 1907.

[4] Eversheim, *Astrophysical Journal*, **26**, 172, 1907; *Zeitschrift für Wiss. Photographie*, **5**, 152, 1907.

[5] Fabry and Perot, *Astrophysical Journal*, **15**, 73, 1902.

[6] Lord Rayleigh, *Phil. Mag.*, **11**, 685, 1906.

[7] Eversheim, *loc. cit.*

[8] Zeeman, *Physikalische Zeitschrift*, **7**, 209, 1908.

made convergent by means of the lens (L), the light is reflected downward by means of the totally reflecting quartz prism (T_1), passes through the interferometer plates (P, Fig. 2), and is once more given a horizontal direction by the quartz prism (T_2). It is next reflected from the plane speculum mirror at N (Fig. 1) to the concave speculum mirror at O which in turn reflects the beam almost at normal incidence and projects it upon the slit (S). As the slit is placed in the principal focus of the concave mirror, and as the latter does not suffer from the defects introduced by chromatic aberration, it is evident that the entire fringe system is brought to a focus simultaneously upon the slit. As the quantity made use of in the final calculation of wave-length is the angular diameter of a fringe, the fringe system upon the slit is so adjusted that the slit lies along a diameter of the rings. By means of a concave mirror at Q a beam of parallel light is made to fall upon the concave grating at G which finally produces a spectrum at F. By using a concave mirror in conjunction with the concave grating it is evident that the spectrum at F consists of monochromatic, non-astigmatic slit images—each image showing its own fringe system. The appearance of photographs as obtained with this arrangement of apparatus is shown in Fig. 3, where the lower reproduction is due to the green and blue lines

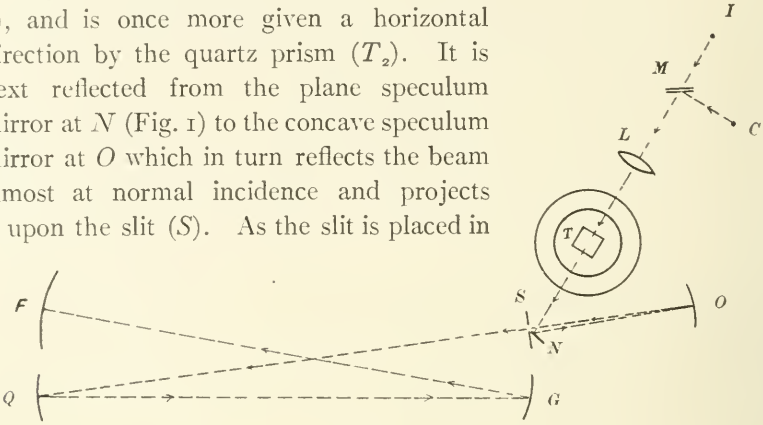

FIG. 1

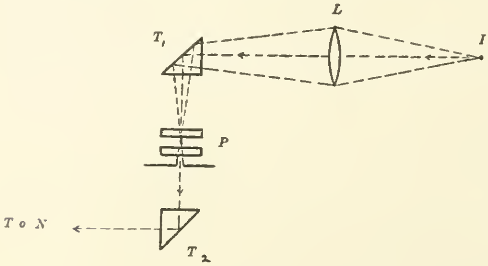

FIG. 2

of cadmium taken with a very wide slit, and the upper, to iron (ratio of enlargement 2.5:1).

The mirror at *O* had a focal length of 20 cm, while the mirror (*Q*) as well as the concave grating (*G*) had a focal length of about 1 meter. In order to bring all of the lines to a sharp focus the photographic film was bent along an arc having a radius of curvature of 50 cm, and in order to avoid astigmatism as much as possible, the grating was so adjusted that a normal drawn from the center of the grating passed through the middle of the photographic film. Furthermore, the length of spectrum photographed was limited to 5 cm on either side of the normal. The range of wave-length recorded on a film 10 cm in length extended, in the first-order spectrum, from 6500 Å. U. to 3500 Å. U. In view of some proposed alterations in the apparatus, the second-order ultra-violet, which practically began at the same wave-length at which the first order ended, was not photographed. In photographing the first-order spectrum a glass lens was placed at *L* and a Seed "ortho" film was used. In view of the fact that these films are not sensitive in the region of the red cadmium line, a small piece of Wratten and Wainwright "panchromatic"

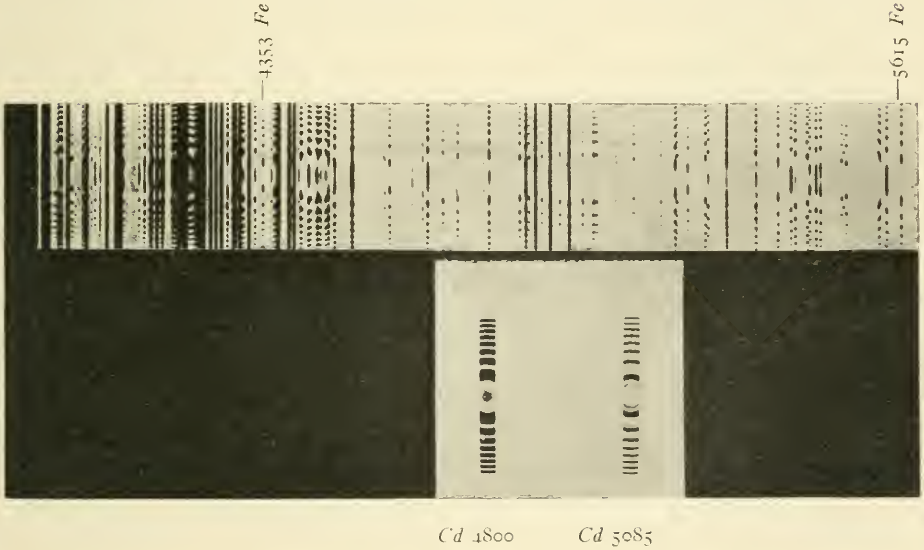

Fig. 3

plate less than 2 cm in width was used to photograph this part of the spectrum.

MOUNTING OF PLATES; CONSTANT-TEMPERATURE BATH

One of the greatest sources of error encountered in the earlier stages of the present investigation was the change in the diameter of the fringe system due to expansion of the "etalon" separating the plates. Using an "etalon" or ring of brass and mounting the plates without any particular precautions against temperature changes, it was found that during an interval of fifteen minutes—the time usually required for a full exposure—the diameter of the fringe system often changed perceptibly and caused a broadening of the photographic record. In order to eliminate once and for all the uncertainties due to temperature changes, the rings were made of invar and the entire system of interferometer plates and invar ring was placed in a constant-temperature bath. That this heroic procedure was effective is shown by the fact that the variations in the diameter of fringes photographed at an interval of more than six hours were too small to be detected on the dividing engine.

The usual type of etalon was used, consisting of a metallic ring which supported three invar studs, equally spaced around the circumference of the ring. The two etalons constructed gave the interferometer plates a separation of 2.654 and 4.427 mm, respectively. The adjustment of the three studs of any one ring to the same length is a comparatively simple matter. The first step consists in filing these studs down so that their lengths, as measured with a micrometer caliper, reading to hundredths of a millimeter, appear the same. The etalon is next placed between the two half-silvered interferometer plates and the transmitted fringe system due to the light coming from a sodium flame is examined. At first the fringes will not be completely circular but will have the appearance of crescents. In order to remedy this defect, the stud lying on the concave side of the crescent is shortened by being rubbed lightly against a smooth piece of wood or paper. The final test to be applied to this adjustment is that the fringes retain the same diameter no matter through what portion of the plates they are viewed. A little practice is sufficient to enable anyone to make the three studs of so nearly the same length that the difference between the longest and the shortest is less than one-quarter of the wave-length of sodium light.

The constant-temperature bath in which the plates were mounted consists of an outer galvanized iron portion (*A*, Fig. 4) which is soldered to a heavy brass tube (*B*) along the edge (*C*). An annular plate of galvanized iron (*D*) covers the top of the tank proper, while two circular plates (E_1) and (E_2) close the ends of the brass tube. The upper brass plate, which is held rigidly in position by two thumbscrews such as *F*, carries the entire interferometer system by means of three brass rods (one of which is shown at *J*). In order to be able to tip the table (*G*) carrying the interferometer plates so as to give the fringes their proper position, the brass rods are threaded at

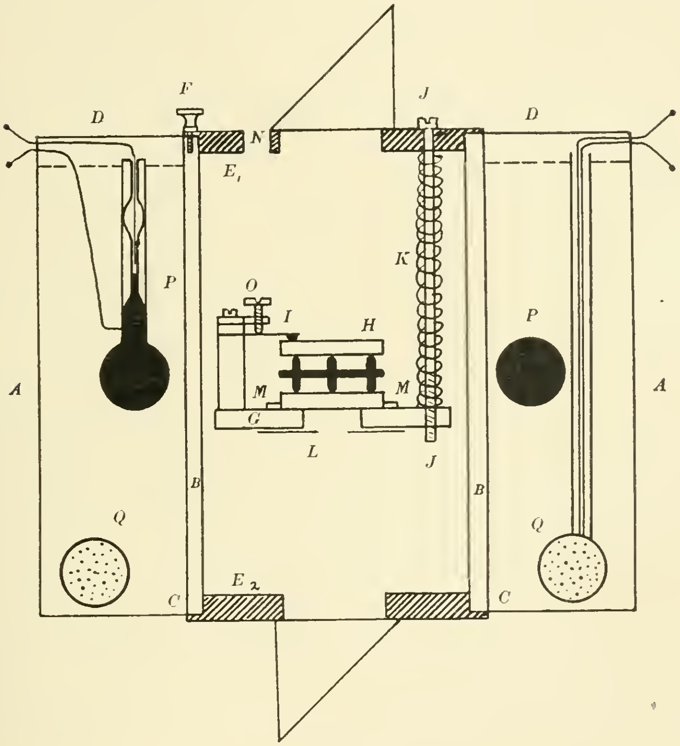

Fig. 4

their lower ends. Rigidity of this portion of the mounting is attained by the use of coil springs (*K*) having a tendency to expand lengthwise. As shown in the diagram, the quartz plates (*H*) are adjusted to parallelism by the well-known arrangement (*I*) due to Fabry and Perot, and are held in position by the brass strips (*M, M*). These brass strips together with a diaphragm at *L* containing a circular opening 4 mm in diameter make it possible to return the plates always to the same position and thus insure using the same portion of the silver film in all cases. Final adjustments for parallelism are made by inserting a small screw-driver through an opening (*N*) and engaging the screw-head (*O*).

The temperature of the plates was kept constant by means of a so-called "electric thermometer"—a device too well known to require description. The outer portion of the tank was filled with water, as it was found that the vapors of kerosene attacked the silver film on the interferometer plates. The temperature-regulating device (*P*) consisted of a glass tube bent into the form of a circle and filled with mercury. A similar glass tube (*Q*) containing oil and numerous strands of German silver wire supplied the necessary heat to the water. By using such a temperature regulator, the temperature of the water (25°0 C.) was kept so nearly constant that the diameters of the fringes did not change perceptibly for hours.

THE SILVER FILM

The two interferometer plates were silvered by means of the well-known Rochelle-salt process, the thickness of silver being such that ten or eleven images could be seen by viewing an ordinary gas-flame through the two mirrors. It was found that these images rapidly assumed a deep, ruby-red color, showing that the number of reflections for red light was much greater than for blue. This is due, not only to the smaller reflecting power of silver for blue light, but also, and to a very marked degree, to a thin, pale-yellow surface film which is always present when silver is deposited chemically. When it is remembered that such a yellow film absorbs blue light very strongly and that the light escaping to form the tenth image has passed through such a film 38 times, it is evident that the removal of this film becomes highly desirable. Heretofore it has been found impossible to polish semi-transparent silver films, for the reason that the silver is scratched or even rubbed off the glass as soon as it is touched. I have succeeded, however, in overcoming these difficulties by proceeding in the following manner:

After silvering the plates, they are placed in an air-bath (at about 45° C.) for an hour and are then polished by means of a toilet "powder-puff," consisting of innumerable fine feathers. After applying "optical" rouge to the puff, its ivory handle is gripped in the chuck of a drill-press or lathe and the entire arrangement is used as a buffing wheel. By proceeding in this manner very thin silver films may be highly polished without scratching. The very gratifying consequence of subjecting a pair of mirrors to a treatment such as this is that the number of reflections is about doubled. The mirrors used in the work here presented showed ten images before and twenty-one after polishing.

SOURCES OF LIGHT

The standard cadmium lines were produced in a Heraeus fused quartz lamp which was continually connected with a mercury air-pump. By running the lamp on as low a current as 3.5 amperes, supplied by a 220-volt direct-current circuit, the sharpness of the red and green lines was splendid. The iron lines were produced by an arc playing between two iron electrodes and also consuming 3.5 amperes supplied by a 220-volt direct-current circuit. The particular type of arc used, which burns with great steadiness and produces lines but little inferior to those of cadmium, has already been described in an earlier publication.[1] In the final calculations of wave-lengths, Michelson's value for the red and green cadmium lines were used.

CALCULATION OF RESULTS

The formula used in the calculation of wave-lengths was that first given by Fabry and Perot. It takes the form

$$\lambda=\lambda_s \frac{P_s}{P}\left(1+\frac{x^2{}_s}{8}-\frac{x^2}{8}\right) \qquad (1)$$

where

λ=unknown wave-length of an iron line

λ_s=wave-length of green *Cd* line (5085.824 Å. U.)

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[1] *Astrophysical Journal*, 27, 296, 1908.

P=order of inner fringe of λ
P_s=order o inner fringe of λ_s
x=angular diameter of inner fringe of λ
x_s=angular diameter of inner fringe of λ_s.

As the angular diameter of an inner fringe is small, it is permissible to replace the angle by its tangent, and therefore, if we represent the linear diameter of a fringe by d and the focal length of the concave mirror which projects the entire fringe system on the slit of the spectroscope by R, we have

$$x=\tan x=\frac{d}{R},$$

whence

$$\lambda=\lambda_s\frac{P_s}{P}\left(1+\frac{d_s^2}{8R^2}-\frac{d^2}{8R^2}\right). \tag{2}$$

As the concave grating (G, Fig. 1) and the concave mirror (Q) were not of identically the same focal length, a slight reduction in the size of the slit image occurred in the focal plane of the concave grating and therefore the diameter of the fringes was less on the photographs than on the slit itself. In order to determine the necessary factor of reduction, two fine parallel lines about 1 cm apart were etched on a piece of glass which was then placed in front of the slit in such a way that the etched lines were in contact with, and ran perpendicular to, the jaws of the slit. Upon photographing the iron spectrum it was found that two very narrow lines, perpendicular to the spectral lines, crossed the entire spectrum. The reduction factor was found by determining the ratio of the separation of these two lines to the separation of the lines etched on the glass plate. In order to facilitate matters in the numerical calculations, d was measured in turns of the screw of the dividing engine and R was reduced to the same units and was multiplied by the above-mentioned reduction factor. Measurements taken over the entire plate showed no perceptible variations in the separation of the two lines, therefore the same value of R applies to all measurements.

For each spectral line the diameters of only the two central fringes were measured as it was found that the outer fringes contributed nothing to the accuracy of the determination. Instead of making a separate wave-length determination for each fringe, the diameter of the inner fringe was calculated from a knowledge of the diameter of the second, according to the relation:

$$d_1^2 = d_2^2 - \frac{8R^2}{P_2} \tag{3}$$

where the subscripts 1 and 2 refer, respectively, to the inner and second fringe. The two values were then averaged and the wave-length calculation was carried out.

ELIMINATION OF PHASE-CHANGE

The true nature of the phase-change which occurs when light is reflected from a metal is not understood and it is only for the sake of convenience that it is looked upon as being due to a penetration of the light into the metallic surface. Placing, then, this interpretation upon the phenomenon of phase-change, it is evident that the true perpendicular distance between the planes at which the light reverses its direction is greater than the separation of the geometrical surfaces of the silver films. Furthermore, as silver is more transparent to blue light than to red, the amount of penetration and hence the separation of the plates will vary throughout the entire spectrum. Instead of actually determining this penetration for any given wave-length it has been found more convenient to calculate the desired correction factor in terms of a small quantity (ϵ) which must be added to or subtracted from the order of the fringe (P) in order to make the penetration the same as that experienced by the standard green *Cd* line—for which ϵ is arbitrarily placed equal to zero. If the wave-lengths throughout the entire spectrum were accurately known, it would be possible to determine ϵ from the measurements obtained with but one etalon. If, for example, we place ϵ_g equal to zero for the green *Cd* line (λ_g), the value of ϵ_r for the red *Cd* line (λ_r) is given by the relation:

$$P_r + \epsilon_r = P_g \frac{\lambda_g}{\lambda_r}\left(1 + \frac{d_g^2}{8R^2} - \frac{d_r^2}{8R^2}\right),$$

whence

$$\epsilon_r = P_g \frac{\lambda_g}{\lambda_r}\left(1 + \frac{d_g^2}{8R^2} - \frac{d_r^2}{8R^2}\right) - P_r . \tag{4}$$

Unfortunately, however, we are sure of the wave-lengths of only the red and green lines of cadmium, and therefore another procedure must be adopted to obtain the values of ϵ throughout the remainder of the spectrum where no accurate wave-length determinations exist. As the amount of penetration, and hence the value of ϵ, does not depend upon the separation of the plates, the effect of penetration may be eliminated, as is shown below, by obtaining measurements for two different separations of the plates. After having evaluated the unknown wave-length (λ), ϵ may be found from either of the two equations (5*a*) or (5*b*). In the following, P and d, and P' and d' refer, respectively, to the larger and the smaller separation of the plates, and λ_s refers to the green cadmium line.

$$P+\epsilon=P_s\frac{\lambda_s}{\lambda}\left(1+\frac{d_s^2}{8R^2}-\frac{d^2}{8R^2}\right) \tag{5a}$$

$$P'+\epsilon=P_s'\frac{\lambda_s}{\lambda}\left(1+\frac{d'^2_s}{8R^2}-\frac{d'^2}{8R^2}\right) \tag{5b}$$

subtracting and solving for λ:

$$\lambda=\lambda_s\frac{P_s\left(1+\frac{d_s^2}{8R^2}-\frac{d^2}{8R^2}\right)-P'_s\left(1+\frac{d'^2_s}{8R^2}-\frac{d'^2}{8R^2}\right)}{P-P'}\,. \tag{6}$$

As the wave-length of the red cadmium line is known, the phase-change for that wave-length was calculated from expression (4). On the other hand, the phase-change for the shortest iron line measured ($\lambda=4282$) was determined from expression (5). These measurements will be given in full later on. Instead of going through the laborious procedure of calculating the phase-change for each line measured, a curve was drawn representing the variations of ϵ with λ and the corrections obtained from this curve were subsequently applied to the measurements given by the greater separation of the plates.

Unless the dispersion of air is taken into consideration no correction need be applied to the measurements as obtained in order to reduce them to standard conditions of temperature and pressure. Calculations show that, for the region of spectrum here investigated, the corrections for the dispersion of air lie entirely below the error of observation and therefore need not be taken into consideration.

NUMERICAL RESULTS

The measurements here given represent an average of a number of complete series of observations. As has been mentioned before, the measurements used in the wave-length calculations of the iron lines were from the photograph taken with the greatest separation of plates, for in this case the fringes were much sharper and the order of fringe was higher.

PHASE-CHANGE

Thin etalon: $2t=5.3084081$ mm. $\frac{1}{8R^2}=0.0000041867$

$\lambda=5085.824$ (*Cd*) $P_g=10{,}437$

$d_1=3.878$ $d_1^2=15.04$

$d_2=6.155$ $d_2^2=37.88$

$$\frac{d_1^2}{8R^2}=0.00006288$$

$$\left.\begin{array}{l} d_1^2=15.04 \\ d_1^2=15.00 \end{array}\right\} 15.02$$

$\lambda=6438.4722$ (*Cd*) $P_r=8{,}244$

$d_1=4.859$ $d_1^2=23.61$

$d_2=7.257$ $d_2^2=52.67$

$$\frac{d_1^2}{8R^2}=0.00009902$$

$$\left.\begin{array}{l} d_1^2=23.61 \\ d_1^2=23.69 \end{array}\right\} 23.65$$

Calculating ϵ_r from expression (4) we find: $\epsilon_r=+0.009$.

PHASE-CHANGE

Thick etalon: $2t=8.8539049$ mm. $\frac{1}{8R^2}=0.0000041867$

$\lambda=5085.824$ (*Cd*) $P_g=17{,}408$

$d_1=3.687$ $d_1^2=13.59$

$d_2=5.230$ $d_2^2=27.35$

$$\frac{d_1^2}{8R^2}=0.00005698$$

$$\left.\begin{array}{l} d_1^2=13.59 \\ d_1^2=13.63 \end{array}\right\} 13.61$$

$\lambda=6438.4722$ (*Cd*) $P_r=13{,}751$

$d_1=3.100$ $d_1^2=9.61$

$d_2=5.196$ $d_2^2=27.00$

$$\frac{d_1^2}{8R^2}=0.00004028$$

$$\left.\begin{array}{l} d_1^2=9.61 \\ d_1^2=9.63 \end{array}\right\} 9.62$$

Calculating ϵ_r from expression (4) we find $\epsilon_r=+0.011$.

Hence we find the average value of the two determinations: $$\begin{array}{r} 0.009 \\ 0.011 \\ \hline +0.010 \end{array}$$

$$\therefore \epsilon_r=+0.010 \text{ for } \lambda=6438.4722$$

PHASE-CHANGE

Thick etalon: $2t=8.8539049$ mm.		$\frac{1}{8R^2}=0.0000041867$	
$\lambda=4282.411$ *Fe* (according to F. & B.)		**P=20,674**	
$d_1=3.507$	$d_1^2=12.30$	$d_1^2=12.30$	12.34
$d_2=4.893$	$d_2^2=23.94$	$d_1^2=12.38$	
	$\frac{d_1^2}{8R^2}=0.00005166$		

Thin etalon: $2t=5.3084081$ mm.		$\frac{1}{8R^2}=0.0000041867$	
$\lambda=4282.411$ *Fe* (according to F. and B.)		**P=12,395**	
$d_1=4.071$	$d_1^2=16.57$	$d_1^2=16.57$	16.53
$d_2=5.981$	$d_2^2=35.77$	$d_1^2=16.49$	
	$\frac{d_1^2}{8R^2}=0.00006921$		

Substituting these values in expression (6) we find

$$\lambda=4282.4117.$$

From expressions (5*a*) or (5*b*) we finally obtain

$$\epsilon=-0.020 \text{ for } \lambda=4282.4117.$$

The variations of phase-change with λ are represented by the continuous curve, Fig. 5; the dotted curve is taken from the work of Fabry and Buisson and the points marked (*R*) and (*E*) are taken, respectively, from the papers of Lord Rayleigh and Eversheim. Although, in all of these cases, the silver was deposited chemically,

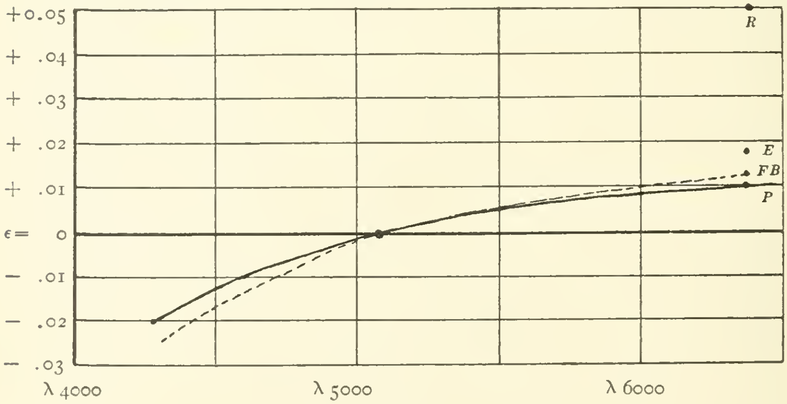

FIG. 5

the values of ϵ for the same wave-length vary enormously, being dependent, as they are, upon the thickness of layer and condition of the surface of the silver film. As it is not possible to reproduce silver films with perfect exactness, it is necessary to determine the values of ϵ for each set of silver films.

The following are the wave-lengths which I have determined, together with those of other observers who have worked on the same iron lines:

I Pfund (1908)	II Fabry & Buisson (1906)	III Fabry & Buisson (1908)	IV Eversheim (1907)
4282.412	.411	.407	.413
4315.094	.093	.089	....
4352.744	.745	.741	....
4427.316	.318	.314	....
4494.574	.576	.572	.581
4531.156	.159	.155	....
4859.757	.759	.756	.761
4878.225	.229	.226	....
4903.327	.327	.324	....
4919.007	.009	.006	....
5001.885	.883	.880	....
5167.495	.495	.492	....
5232.958	.960	.958	.963
5434.531	.532	.530	....
5455.617	.618	.616	....
5497.523	.523	.521	....
5506.784	.785	.783	....
5586.772	.772	.770	....
5615.659	.660	.658	....
6191.568	.570	.569	....
6230.731	.733	.732	....
6393.611	.612	.613	....
6494.992	.994	.994	....

To show how the values of the wave-lengths were obtained, a typical calculation is given in full.

$\lambda = 5506.785$ *Fe* (according to F. and B.)

Thick etalon: $2t = 8.8539049$ mm. $P = 16{,}077$

$\epsilon = +0.005$

$$d_1 = 4.170 \qquad d_1^2 = 17.39 \qquad \left.\begin{array}{l} d_1^2 = 17.39 \\ d_1^2 = 17.50 \end{array}\right\} 17.445$$

$$d_2 = 5.688 \qquad d_2^2 = 32.35$$

$$\frac{d_1^2}{8R^2} = 0.00007304$$

For $\lambda=5085.824$ (*Cd*): $P=17,408$ $\frac{d_1^2}{8R^2}=0.00005698$, $\epsilon=+0.000$

$17,408\div16,077.005=1.08278874$

$$\begin{array}{r} 1.00005698 \\ .000\ 7304 \\ \hline 0.99998394 \end{array}$$

$$\lambda=5085.824\times1.08278874\times0.99998394$$
$$\lambda=5506.784$$

ACCURACY OF RESULTS

The accuracy of wave-length determinations is largely dependent upon the degree of accuracy to which the diameters of the fringes may be determined. As a result of my experience I have found that successive readings on a well-developed inner ring may be repeated with an error not greater than 1 part in 500 to 600. However, this is not a fair test. My estimate of the accuracy of measurement is based upon a comparison of results obtained at an interval of about 24 hours (so as to eliminate the effect of visual memory) and also upon a calculation of the differences in the squares of the diameter of successive rings (which ought to be constant and equal to $\frac{8R^2}{P}$). As a result of these tests I am forced to the conclusion that the highest accuracy which may be claimed for the diameters of fringes used in the work here presented, is a little better than 1 part in 150, corresponding in the average to 0.004 Å. U.

From the table of numerical results it will be observed that the agreement between the results of different observers is fairly satisfactory. The results of Eversheim are also given, but a comparison between his results and the others is, perhaps, not just, as the greater part of his work was carried out on the more refrangible side of the green cadmium line where he himself had made no determinations of phase-change. Attention is to be called to the fact that while columns I, II, and IV, are based on Michelson's value of the wave-length of the red cadmium line ($\lambda=6438.4722$), column III is based upon the later determination of Fabry and Benoit ($\lambda=6438.4696$). In order to reduce the results of columns I and III to the same basis it is necessary to subtract about 0.0020 Å. U. from column I. Upon making this change it is found that the difference between these two columns nowhere exceeds 0.004 Å. U.

In attempting to calculate the phase-change (ϵ) for the blue cadmium line, Michelson's values were substituted in expression (4) and it was invariably found that ϵ was greater than zero instead of less than zero. The fact that Lord Rayleigh and Eversheim have found similar irregularities would seem to point to the conclusion that Michelson's value for the blue cadmium line (4799.9107) is too small. It is to be considered that this line is not single but is made up of a complex of at least three lines and although Michelson's determination of the center of gravity of this complex at the separation of plates used by him, is undoubtedly correct, it seems inadvisable at the present time to use this line in accurate wave-length determinations.

The accuracy of the results here presented is by no means the highest of which the method is susceptible. The main fault to be found with the apparatus used, lies in the small dispersion of the grating and the small diameter of the inner fringes. Without going into these matters in detail, suffice it to say that the next step to be taken will consist in reconstructing the apparatus, using mirrors of longer focus, a grating of larger dispersion, and etalons giving the interferometer plates a greater separation. In addition to this, an attempt will be made to deposit films of speculum metal or magnalium by cathode discharge so that the fringes in the ultra-violet may compare in narrowness with those in the visible spectrum. By making these changes it is hoped that the wave-lengths of the iron lines may eventually be established to within 0.001 or 0.002 Å. U.

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Johns Hopkins University
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NOTES ON THE DETERMINATION OF THE ORBITS OF SPECTROSCOPIC BINARIES

By H. C. PLUMMER

1. The determination of the elements of a spectroscopic binary system is usually facilitated by the fact that observations have been made over a time long enough to fix the period with considerable accuracy and with sufficient care in the distribution of them to make known fairly precisely the extreme range in the variation of the radial velocity. With these data it is a fairly simple matter to determine from the velocity curve the other circumstances of the orbital motion, and a large number of practical methods have been proposed. It is needless to discuss their relative advantages: the method which gives the best results in one case may well be unsuitable in another. Under unfavorable circumstances any method by itself is liable to give untrustworthy results. As several methods are available which can be applied very easily and quickly, the best plan would seem to be to determine the approximate elements in several independent ways. The degree of accordance between the results so obtained will be a valuable guide to the judgment and may well save much labor which is sometimes spent in calculating trial ephemerides. It may therefore be useful to describe these methods briefly in a more connected and, incidentally, perhaps more general form than that in which they originally appeared. The notation adopted is as far as possible that which has come into general use.

2. The periods of spectroscopic binaries are most commonly short enough to be reckoned in days and the measured radial velocities are now invariably recorded in kilometers per second. Hence a natural and consistent system of units to adopt is:

Unit of time = 1 mean solar day;
Unit of length = 86400 km = 0.000578 astronomical units;
Unit of velocity = 1 km per second;
Unit of mass = that of the sun.

Velocities of approach are considered negative.

3. The radial velocity measured at any time t is

$$V=\gamma+Ke\cos\omega+K\cos u$$
$$=\gamma'+K\cos u,$$

where γ is the velocity relative to the sun of the center of mass of the system, K is the semi-amplitude of the velocity curve, u is the longitude in the orbit measured from the receding node in the direction of the motion, ω is the longitude of periastron, and e is the eccentricity. Let U be the period, and $\mu=2\pi U^{-1}$ the mean daily motion, and T the time of periastron passage. The quantities U, T, K, γ or γ', ω, and e may be regarded as the six elements which can be determined by spectroscopic observations. The inclination of the orbit cannot be so determined, while any possible information as to the size of the orbit and the masses can be deduced from the quantities defined.

4. The velocity curve may be referred to two axes, perpendicular to the axis of velocities, each of which has its advantages. The first is $V=\gamma'$ which lies midway between the maximum and minimum velocities. The maximum and minimum points A, B on the velocity-curve require $u=0°$ or $180°$; that is, they correspond to the receding and approaching nodes, respectively. The points where $V=\gamma'$ crosses the curve, E, F, require $u=90°$ and $270°$, that is, they correspond to the extremities of the focal chord at right angles to the line of nodes. The points A, E, B, F thus divide the velocity-curve into four parts corresponding to focal quadrants bounded by the line of nodes.

The second axis is the line $V=\gamma$ which, as was first pointed out by Rambaut, bisects the area of the velocity-curve. The points C, D where $V=\gamma$ crosses the curve require that the velocity relative to the center of mass shall be zero; that is, they correspond to the points on the orbit where the tangents are parallel to the line of nodes. The points $ACBD$ divide the curve into four parts such that the area from A to C equals that from C to B, and that from B to D equals that from D to the following maximum. These areal conditions impose a check on the drawing of the velocity-curve, especially in regard to the position of the maximum and minimum, and this reason alone makes it useful to determine the position of the line $V=\gamma$ by some planimetric process.

5. The points on the velocity-curve corresponding to certain im-

portant points of the orbit can be found very easily. Those corresponding to periastron and apastron, P_1, P_2, are determined by the following conditions: (1) their abscissae differ by $\frac{1}{2}U$; (2) their ordinates measured from $V=\gamma'$ are equal and opposite, for $u=\omega$ and $180°+\omega$; (3) the periastron point must lie in the shortest and the apastron point in the longest time interval in which the curve is divided at *AEBF*. The points L_1, L_2, corresponding to the extremities of the latus-rectum, are determined by these conditions: (1) they are equidistant in time from P_1, (2) their ordinates measured from $V=\gamma'$ are equal and opposite, for $u=\omega+90°$ and $\omega+270°$. And, generally, any pair of points which lie in alternate sections of the curve as determined by *AEBF* and have equal and opposite γ'-ordinates correspond to the extremities of a focal chord. The points corresponding to the extremities of the minor axis, K_1, K_2, are determined by the conditions: (1) they are equidistant in time from P_1; (2) their ordinates measured from $V=\gamma$ are equal and opposite, for the corresponding velocities relative to the center of mass are parallel, equal, and opposite. Simple methods of finding the special points mentioned by means of the intersection of the curve with a suitably superposed copy have been given by Schwarzschild and by Zurhellen: they can, however, be found very easily by simple trial and error. The points *C*, *D* themselves correspond to the extremities of the diameter conjugate to the diameter which is parallel to the line of nodes since the corresponding orbital velocities are parallel to this line.

6. Let t_1 be the time at a point on the branch *AEB* of the curve and v and E_1, the corresponding true and eccentric anomalies. Let $180°+v$ and E_2 be the true and eccentric anomalies of the other end of the same focal chord, and t_2 the time at the corresponding point on the second part of the velocity curve. Then:

$$(1-e)^{\frac{1}{2}} \tan \tfrac{1}{2}v=(1+e)^{\frac{1}{2}} \tan \tfrac{1}{2}E_1 \; ; \quad \mu(t_1-T)=E_1-e \sin E_1 \; ;$$
$$-(1-e)^{\frac{1}{2}} \cot \tfrac{1}{2}v=(1+e)^{\frac{1}{2}} \tan \tfrac{1}{2}E_2 \; ; \quad \mu(t_2-T)=E_2-e \sin E_2 \; .$$

Hence

$$-(1-e)=(1+e) \tan \tfrac{1}{2}E_1 \tan \tfrac{1}{2}E_2 \, ,$$

or

$$e \cos \tfrac{1}{2}(E_2+E_1)=\cos \tfrac{1}{2}(E_2-E_1).$$

Consequently

$$\mu(t_2-t_1)=E_2-E_1-2e\sin\tfrac{1}{2}(E_2-E_1)\cos\tfrac{1}{2}(E_2+E_1)\,,$$
$$=(E_2-E_1)-\sin(E_2-E_1)\;;$$

from which E_2-E_1 can be found easily, especially with the help of the table given by Schwarzschild. Again

$$\tan\tfrac{1}{2}(E_2-E_1)=-\frac{(1-e^2)^{\frac{1}{2}}}{2e}(\cot\tfrac{1}{2}v+\tan\tfrac{1}{2}v)\,,$$
$$=-\cot\phi\operatorname{cosec}v\,,$$

where $\sin\phi=e$.

7. Let now t_3, t_4 be the times at the ends of the perpendicular focal chord, so that the true anomalies are $v+90°$ and $v+270°$. The corresponding points on the velocity-curve can always be found by the conditions that they fall in the intermediate quadrants to the first pair and the sum of the squares of the γ'-ordinates of two points belonging to the different pairs is K^2. Then the two pairs will give:

$$\mu(t_2-t_1)=2\eta-\sin 2\eta\;;\quad \tan\phi\sin v=-\cot\eta$$
$$\mu(t_4-t_3)=2\eta'-\sin 2\eta'\;;\quad \tan\phi\cos v=-\cot\eta'.$$

Hence we can find ϕ or the eccentricity and $v=u-\omega$. But this gives ω, for the γ'-ordinate corresponding to t_1 is $K\cos u$ and therefore gives u. Further, two independent values of T will be given by the equations

$$\tan\tfrac{1}{2}E_1=\tan(45°-\tfrac{1}{2}\phi)\tan\tfrac{1}{2}v;\qquad \mu(t_1-T)=E_1-e\sin E_1$$
$$\tan\tfrac{1}{2}E_3=\tan(45°-\tfrac{1}{2}\phi)\tan(45°+\tfrac{1}{2}v);\quad \mu(t_3-T)=E_3-e\sin E_3\,.$$

8. This general method can be applied to special pairs of points. Thus AB, EF are two such pairs, and in this case we have simply $v=-\omega$. The times of maximum and minimum velocity, however, are not always very exactly determined. Other two pairs of points are those for which the γ'-ordinates are $\pm K/\sqrt{2}$. In this case $u=45°$ and $v=45°-\omega$. Here the curve is usually steep and the corresponding times are well determined. Good results can accordingly be expected from this application of the method. Finally we have the points P_1P_2, L_1L_2, for which $v=0°$. Here the γ'-ordinates are $\pm K\cos\omega$, and $\pm K\sin\omega$, giving ω, and $t_1=T$. Also $\phi=\eta'-90°$, giving e. This is the elegant method of Schwarzschild as simplified by Nijland and Zurhellen. In this case there is no independent determination of T, the last equation of the preceding paragraph reducing in effect to $2T=t_3+t_4$.

9. From the properties of a focal chord we may turn to the properties of a diameter of the orbit. Let t_1, t_2 be the times of passing the ends of a diameter and let $E+\frac{1}{2}\pi$, $E+\frac{3}{2}\pi$ be the corresponding eccentric anomalies, E being the eccentric anomaly of the end of the conjugate diameter. Then

$$\mu(t_1-T)=E+\tfrac{1}{2}\pi-e\cos E,$$
$$\mu(t_2-T)=E+\tfrac{3}{2}\pi+e\cos E,$$

whence

$$\tfrac{1}{2}\mu(t_1+t_2-2T)=E+\pi,$$
$$\mu(t_2-t_1-\tfrac{1}{2}U)=2e\cos E.$$

Now it has been seen that C, D, where the curve meets the γ-axis, are such a pair of points, the conjugate diameter being parallel to the line of nodes. Hence

$$-\tan\omega=\cos\phi\tan E,$$
$$=\cos\phi\tan\tfrac{1}{2}\mu(t_1+t_2-2T)\,,$$

and

$$-e=\tfrac{1}{2}\mu(t_2-t_1-\tfrac{1}{2}U)\sec\tfrac{1}{2}\mu(t_1+t_2-2T)\,,$$

as given by Zurhellen; and by eliminating T,

$$\tfrac{1}{2}\mu(t_2-t_1-\tfrac{1}{2}U)=e\cos\phi\,(\cos^2\phi+\tan^2\omega)^{-\frac{1}{2}}\,,$$
$$=e\cos\omega\,(1-e^2\cos^2\omega)^{-\frac{1}{2}}\cos\phi\,,$$

as given by Lehmann-Filhés for the determination of ϕ or e when $e\cos\omega$ has already been determined and e is not small. Again K_1, K_2, the ends of the minor axis, are such a pair of points. Here $E=0$, and hence

$$e=\tfrac{1}{2}\mu(t_2-t_1-\tfrac{1}{2}U)\,.$$

Also the radial components of the velocities at the ends of the minor axis are $\pm K\cos\phi\sin\omega$, and these quantities will therefore be given by the γ-ordinates at K_1, K_2. These properties have also been given by Zurhellen.

10. Let z_1, z_2 be the areas, taken positively, between the curve and the γ-axis from A to C and from B to D respectively. These are the projections on the plane containing the line of sight and the line of nodes of the perpendiculars from C and D in the orbit on the line of nodes. Hence we obtain

$$\tfrac{1}{2}(z_1+z_2)=K\mu^{-1}\cos\phi\,(1-e^2\cos^2\omega)^{\frac{1}{2}}\,,$$
$$\tfrac{1}{2}(z_1\sim z_2)=K\mu^{-1}\cos\phi\cdot e\sin\omega\,.$$

The method of Lehmann-Filhés uses only the ratio of these quantities and the unit in which the areas are measured is immaterial. But by measuring a rectangle with given sides it is easy to find the planimeter value for an area of 1 km/sec. by 1 day and so to evaluate the areas in the proper units. Then we have e determined by the equation

$$z_1 z_2 = K^2 \mu^{-2} \cos^4 \phi \, ,$$

and ω is determined by the second of the previous equations. Thus ω and e can be determined directly from the areal properties of the velocity-curve, and we also have

$$\gamma' - \gamma = Ke \cos \omega \, .$$

11. If ψ is the angle between the tangent to the velocity-curve and the time-axis,

$$\tan \psi = \frac{dV}{dt} = -K \sin u \frac{dv}{dt}$$
$$= -\mu K \cos \phi \sin u \cdot a^2 r^{-2} \, .$$

where a is the mean distance in the actual orbit and r is the radius-vector of the corresponding point. Now $\cos u$ is given by the γ'-ordinate of the point on the velocity-curve. Hence by drawing tangents to this curve at a number of points it would be quite possible to reconstruct the actual orbit on an arbitrary scale by the polar co-ordinates of its points: for

$$v = u - \omega \, ; \quad r \propto (\sin u \cot \psi)^{\frac{1}{2}} \, .$$

The method seems practical but rather long: its interest lies in the analogy to Sir John Herschel's method for double stars by which, through distrust of the measured distances, he constructed the apparent orbit from the position-angles alone. Without going so far as to construct the orbit in this way, however, useful information may be obtained from the direction of the velocity-curve at special points. Zurhellen has shown how the eccentricity can be derived from the directions at the periastron and apastron points, which is only one particular case. We have in general

$$\tan \psi = -\mu K \sec^3 \phi \sin u (1 + e \cos v)^2 \, ;$$

and thus at

A, B: $u = 0°, 180°$; $\tan \psi = 0$
E, F: $u = 90°, 270°$; $\tan \psi = \mp \mu K \sec^3 \phi (1 \pm e \sin \omega)^2$.
P_1, P_2: $u - \omega = 0°, 180°$; $\tan \psi = \mp \mu K \sec^3 \phi \sin \omega (1 \pm e)^2$.
L_1, L_2: $u - \omega = 90°, 270°$; $\tan \psi = \mp \mu K \sec^3 \phi \cos \omega$.
K_1, K_2: $u - \omega = 90° + \phi, 270° - \phi$; $\tan \psi = \mp \mu K \cos \phi \cos (\omega \pm \phi)$.

The angle ψ is correctly obtained from the curve only when it is drawn to the same scale in time and velocity, e. g., in the units 1 day and 1 km/sec. If a different scale is used in the two directions, allowance must be made for this fact in finding tan ψ, although it is not material when only the ratio of two such expressions is used.

12. When the eccentricity is small, the velocity-curve approaches in form the simple sine-curve and graphical methods cease to be of value. It is then that the analytical method becomes useful. The observations may be represented by a series

$$\begin{aligned} V=b_0+b_1 \cos \mu t+b_2 \cos 2\mu t \\ +a_1 \sin \mu t+a_2 \sin 2\mu t \,, \end{aligned}$$

the coefficients in which can be calculated either by some method of harmonic analysis or by least squares. The period being supposed known, the five terms are all that are required to determine the other five elements of the orbit. Now

$$\begin{aligned} V&=\gamma+K(e \cos \omega+\cos u)\,, \\ &=\gamma+K \cos^2 \phi \cos \omega \cdot \frac{\cos E}{1-e \cos E}-K \cos \phi \sin \omega \cdot \frac{\sin E}{1-e \cos E}\,, \\ &=\gamma+K \cos^2 \phi \cos \omega \sum_{j=1} c_j \cos jM-K \cos \phi \sin \omega \sum_{j=1} s_j \sin jM\,, \end{aligned}$$

where $M=\mu(t-T)$ is the mean anomaly. Here

$$\begin{aligned} c_j&=\frac{1}{\pi}\int_0^{2\pi} \frac{\cos E}{1-e \cos E} \cos jM\, dM\,, \\ &=\frac{1}{\pi}\int_0^{2\pi} \cos E \cos (jE-je \sin E)dE\,, \\ &=J_{j+1}(je)+J_{j-1}(je)=2e^{-1}J_j(je)\,; \\ s_j&=\frac{1}{\pi}\int_0^{2\pi} \frac{\sin E}{1-e \cos E} \sin jMdM\,, \\ &=\frac{1}{\pi}\int^{2\pi} \sin E \sin (jE-je \sin E)dE\,, \\ &=J_{j-1}(je)-J_{j+1}(je)=\frac{2d \cdot J_j(je)}{d(je)}\,, \end{aligned}$$

where J_j is a Bessel's function of order j.

$$J_j(x)=\frac{x^j}{2^j j!}\left\{1-\frac{x^2}{2(2j+2)}+\frac{x^4}{2\cdot 4\cdot (2j+2)(2j+4)}-\dots\right\}$$

Hence by comparison with the series of which the coefficients have been calculated, $b_0=\gamma$ and

$$a_j=2e^{-1}K\cos^2\phi\cos\omega\, J_j(je)\sin j\mu T-2K\cos\phi\sin\omega\, J'_j(je)\cos j\mu T\,;$$
$$b_j=2e^{-1}K\cos^2\phi\cos\omega\, J_j(je)\cos j\mu T+2K\cos\phi\sin\omega\, J'_j(je)\sin j\mu T\,.$$

The four equations obtained by making $j=1$ and $j=2$ will give K, T, e, and ω by successive approximations. When the first power of e alone is retained, $J_1(e)=\frac{1}{2}e$, $J_2(2e)=\frac{1}{2}e^2$, $J'_1(e)=\frac{1}{2}$, $J'_2(2e)=\frac{1}{2}e$ and $\cos\phi=1$. Hence the equations in this case reduce to those given by Wilsing:

$$a_1=-K\sin(\omega-\mu T)\,,\quad b_1=K\cos(\omega-\mu T)\,;$$
$$a_2=-eK\sin(\omega-2\mu T)\,,\ b_2=eK\cos(\omega-2\mu T)\,.$$

The first approximation to e is therefore given by

$$e^2=(a_2{}^2+b_2{}^2)\div(a_1{}^2+b_1{}^2)\,.$$

The development of further approximations has been discussed by Russell. Except when the eccentricity is small this method offers in general no advantage over the graphical methods.

13. When approximate values of the elements have been obtained by any of the foregoing methods, or from any combination of them, the good quality of the observations may justify a final solution by the method of least squares. The form of the equations of condition has been given by Lehmann-Filhés. For completeness they are given here in what seems a slightly simplified form. Let n be the number of periods over which the observations extend, and let

$$w=-K\delta\omega\,,\quad \epsilon=-K\sec^2\phi\,\delta e\,,$$
$$\tau=\mu K\sec^3\phi\cdot\delta T\,,\quad \nu=-nKU\sec^3\phi\cdot\delta\mu\,.$$

Then the equations of condition become

$$\begin{aligned}V_o-V_c=\delta\gamma'&+\cos u\,\delta K+\sin u\cdot w\\&+\sin u\sin v\,(2+e\cos v)\cdot\epsilon\\&+\sin u\,(1+e\cos v)^2\,\tau+\sin u\,(1+e\cos v)^2\,\frac{t-T}{nU}\nu\,.\end{aligned}$$

In this form no further transformation seems necessary in order to secure homogeneity in the coefficients. After the corrections to the elements have been found, γ can be recalculated from the new values since its correction is not included explicitly in the equations of condition.

14. When the elements as already defined have been determined, some information in regard to the size and masses of the system can be deduced, but only in terms of the inclination, which spectroscopic observations alone leave unknown. Let $i (< 90°)$ be the angle between the line of sight and the normal to the plane of the orbit. Then

$$a \sin i = K\mu^{-1} \cos \phi \cdot 86400 \text{ km} ,$$

$$m'^3(m+m')^{-2} \sin^3 i = K^3\mu^{-1} \cos^3 \phi \cdot [3.81445-10] ,$$

where the sun's mass is unity, m is the mass of the star whose radial velocity has been observed, and m' is the mass of the other star. If the radial velocity V' of the second component of the binary system is measured at the same time,

$$m(V-\gamma)+m'(V'-\gamma)=0 .$$

One such equation will give $m:m'$ when γ is known and two will give γ in addition without any knowledge of the orbit. It is assumed that the velocities have been determined by means of a comparison spectrum; if no comparison spectrum has been used and only the relative velocities of the two components have been determined from the positions of corresponding lines in the two superposed spectra, by a' must be understood the mean distance in the relative orbit instead of the mean distance of one component about the center of mass, and for the expression $m'^3 (m+m')^{-2}$ above must be substituted $(m+m')$.

15. The relation of spectroscopic observations to the visual orbit may be briefly considered. If visual observations have been made over a sufficiently long time to determine the elements, the inclination i is known and also the mean distance a'' expressed in seconds. Let a and a' be the mean distances of the components about the center of mass, expressed in the linear unit adopted, 86400 km, so that

$$ma = m'a' = \frac{mm'}{m+m'}(a+a')$$
$$= \frac{mm'}{m+m'} \cdot \frac{a''}{\pi''} \cdot [3.23813] ,$$

where π'' is the parallax. Hence

$$V = \gamma + K(e \cos \omega + \cos u)$$
$$= \gamma + \mu\, a \sec \phi \sin i (e \cos \omega + \cos u)$$
$$= \gamma + [3.23813] \cdot \mu \sec \phi \sin i (e \cos \omega + \cos u) \cdot \frac{a''}{\pi''} \cdot \frac{m'}{m+m'} ;$$

and similarly for the second component

$$V'=\gamma-[3.23813]\cdot\mu\sec\phi\sin i(e\cos\omega+\cos u)\cdot\frac{a''}{\pi''}\cdot\frac{m}{m+m'}\,.$$

Thus if the spectrum of only the first component can be measured at different times, it is only possible to determine γ and $(1+m/m')\,\pi''$. The relative velocity alone

$$V-V'=[3.23813]\cdot\mu\sec\phi\sin i(e\cos\omega+\cos u)\,a''/\pi''$$

will give the parallax and the sum of the masses, for

$$m+m'=[3.52884]\mu^2(a''/\pi'')^3\,.$$

But if the velocities of the two components are determined by reference to a comparison spectrum the ratio of the masses and hence the masses themselves, compared with the sun, can also be determined.

16. The ambiguity regarding the position of the plane of the orbit as determined by visual observations can be removed, as is well known, only by measures of the radial velocity. It will be supposed that i, as previously defined, is a positive angle less than 90°. Let m be the mass of the principal star and m' that of the companion. There is much confusing variety in the notation employed by the computers of double-star orbits, but we may assume the system in which ρ, θ, the distance and position-angle, are given by

$$\rho\cos(\theta-\Omega)=r\cos(v+\lambda)\,,$$
$$\rho\sin(\theta-\Omega)=\pm r\sin(v+\lambda)\cos i\,,$$

where Ω is the position-angle of the node falling between 0° and 180°, λ is the longitude of periastron measured from this node in the direction of the orbital motion; and as regards the double sign the upper corresponds to direct and the lower to retrograde motion of the companion. The question now is whether λ and ω are identical or whether they differ by 180°? The data required for the answer may be either (1) V_1, V_2, the radial velocities of the principal star at different times, or (2) V, V', the radial velocities of the two stars at the same time. Then it is easily seen that if

$$V_1-V_2 \text{ and } \cos(v_1+\lambda)-\cos(v_2+\lambda)$$

or if

$$V-V' \text{ and } e\cos\lambda+\cos(v+\lambda)$$

are of the same sign, $\lambda=\omega$; if of opposite sign, $\lambda=\omega+180°$. In the former case the receding node of the principal star corresponds to the companion at Ω, i. e., the companion is approaching the observer when at its first node; in the latter case the companion is receding at Ω. This way of regarding the question differs slightly from the point of view adopted by Dr. Campbell (*Lick Observatory Bulletin,* No. 70) but it seems to involve less disturbance of the system of elements universally adopted by the spectroscopists on the one side and that adopted by the majority of the computers of visual orbits on the other.

17. Reference has been made in the foregoing to the following papers:

Rambaut, *Monthly Notices*, **51**, 316, 1891.
Lehmann-Filhés, *Astronomische Nachrichten*, **136**, 17, 1894.
Schwarzschild, *ibid.*, **152**, 65, 1900.
Nijland, *ibid.*, **161**, 103, 1903.
Zurhellen, *ibid.*, **175**, 245, 1907.
Wilsing, *ibid.*, **134**, 89, 1894.
Russell, *Astrophysical Journal*, **15**, 252, 1902.

In addition to these may be mentioned the recent paper by King (*Astrophysical Journal*, **27**, 125, 1908), and for a more detailed account of the better known methods, that by H. D. Curtis (*Pub. A.S.P.*, **20**, 133, 1908).

MT. HAMILTON
May 1908

SERIES IN THE SPECTRUM OF BARIUM

By F. A. SAUNDERS

The spectrum of barium has been studied by Kayser and Runge (*Wied. Ann.*, **43**, 385, 1891), Rydberg, Exner and Haschek, Hermann (*Annalen der Physik*, **16**, 684, 1905), and others. Kayser remarks (*Handbuch der Spectroscopie*, **2**, 541) that no series have been found in this spectrum, though several triplets were noticed. Rydberg (*Wied. Ann.*, **52**, 126, 1894) mentions such triplets, and gives the proper values for their "width" on a wave-number scale. I have not, however, been able to find any published work showing the wave-lengths of the lines of these triplets, nor how they are arranged in series. Since the triplets in the spectra of calcium and of strontium are conspicuous, one would naturally expect to find them easily in barium. That they have not been found long ago is in itself proof that they are neither very strong nor very striking.

The writer has taken a good set of photographs of the spectrum of barium, extending from λ 8000 to λ 1900. A parabolic concave grating[1] was used to λ 2300 and a quartz spectrograph for the rest. The arc was the main source of light, though some spark spectra were also obtained for comparison. Graphite rods were used as terminals, and the best barium chloride obtainable on the market as the source of barium. The graphite rods contain *Ti* in small quantities, and spectroscopic traces of *Al, Bo, Cu, Si, Ca,* and *Na* were nearly always present also. The barium salt contributed *Sr* to the list of impurities. The presence of these foreign substances was rather an advantage than otherwise, as their lines served as standards, being always sharp, and they were by no means so numerous as to be in the way. None of the new lines added to the barium list is sharp; they cannot therefore be confused with the lines due to impurities, and, indeed, the excellent lists of Exner and Haschek make such confusion very unlikely. Check photographs of the spectra of the impurities were

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[1] This equipment is described in the *Astrophysical Journal*, **20**, 188, 1904. It is a pleasure to express again my indebtedness to the Rumford Fund Committee for the grant which made it possible to purchase this magnificent instrument.

used for comparison, when necessary. The great cyanogen bands were very much in the way, and I was forced to take several photographs, using the barium salt on rods of *Cu* or *Al* in order to be able to find the fainter lines in these regions.

My red-end photographs show many lines that were new at the time they were measured. The excellent measurements of Hermann in this region make it unnecessary for me to publish my figures at present. Only three red lines are used in the series arrangement; my measurements for these gave λ 7906.0; 7392.6; and 7195.5; Hermann gives λ 7906.13; 7392.83; and 7195.71. The agreement is, under the circumstances, satisfactory. A complete list of the lines of the barium spectrum was prepared, the wave-lengths reduced to vacuum, and the reciprocals taken. These wave-numbers were then plotted on a large scale. To find triplets of constant frequency-difference reduced itself to finding lines at constant distances apart, and the work was made much easier.

With the information thus available, it proved to be easy to find three complete triplets of the second subordinate series, and fragments of two more followed later. Analogy then led me to search for a strong member of the first subordinate series in the green, but here a difficulty was encountered. The only possible group included the great line λ 5535 as one of its members. But this was clearly out of the question, since this is a Bunsen flame line, totally different in its characteristics from the typical series lines. A careful examination of this line under fairly high dispersion made it seem likely that it was double; that is, that the line I sought was present beside the line λ 5535. The new line was too faint to be seen when λ 5535 was sharp, since this occurs only with very small amounts of barium in the arc; and, when a large quantity of barium was introduced, the stronger line spread out so far that it obliterated the weaker one entirely. The best conditions for observing the line are therefore when λ 5535 is of medium strength, and feebly reversed, if at all. It then appears and behaves like its neighbor λ 5519, which belongs to the same series triplet. It was not possible to regulate the quantity of barium so exactly as to be able to keep these conditions constant and photograph the new line. Feeling that the dispersion available was not sufficient for exact eye measurements, I asked Professor N. A.

Kent of Boston University, who is working with a 21-foot grating, if he would kindly examine λ 5535 for me. Without being informed of the position of the new line, he independently discovered it, and measured its wave-length in the second-order spectrum, with the result 5536.07 (the main line being 5535.69). This agrees almost exactly with the value which I had in the meantime predicted for it from the triplet spacing. Professor Kent took great pains to identify the lines near by and thus to show that the new line really belonged to barium. For the very generous manner in which he placed his time at my disposal, and for the great care and skill with which he made these observations, I wish to record my sincerest gratitude.

This first subordinate triplet being then complete, there was little difficulty in tracing out the others. None of them is so prominent as one might expect, and some of the necessary lines had escaped previous observation through faintness, or by hiding behind the cyanogen bands.

The two subordinate series are tabulated below, arranged according to Rydberg's scheme, so as to show the constancy of wave-number differences. All the wave-numbers are corrected to vacuum.

TABLE I

First Subordinate Series of Barium

λ	1/λ	ν	λ	1/λ	ν	λ	1/λ
5819.21	17179.8	878.0	5536.07	18058.4	370.4	5424.82	18428.8
	55.4			54.7			
5800.48	17235.2	877.9	5519.37	18113.1			
	127.6						
5777.84	17302.8						
			4333.04	23072.2	371.0	4264.45	23443.2
				52.7			
4493.82	22246.7	878.2	4323.15	23124.9			
	21.4						
4489.50	22268.1						
			3947.6	25325.0		A	
				12.8			
4087.53	24458.1	879.7	3945.6	25337.8			
	15.3						
4084.94	24473.4						
3895.2	25665.4	870	3767.5	26536		B	
3787	26399						

TABLE II

SECOND SUBORDINATE SERIES OF BARIUM

λ	$1/\lambda$	ν	λ	$1/\lambda$	ν	λ	$1/\lambda$
7906.0	12645.0	878.4	7392.6	13523.4	370.3	7195.5	13893.7
4903.11	20389.6	878.3	4700.64	21267.9	370.3	4620.19	21638.2
4239.91	23578.9	879.2	4087.53	24458.1	370.1	4026.57	24828.2
3975.55	25146.8		C				
3841.72	26022.8						

The columns of these tables which are headed ν contain the wave-number differences, which should be constant. The numerous gaps are due to the excessive faintness of the lines. The lines toward the end of the first series are nearly all new, but their wave-lengths are very inaccurate. The line λ 3841 of the second series is also new. The line λ 4087 appears to belong to both series; calculation shows that two lines occur here, only 0.4 Å apart; since both are diffuse, I could not separate them. At the place marked *A*, the line λ 3890.64 is calculated to appear, but the strong barium lines 3891.97 and 3889.45 blot it out. At the place *B* there is a faint haze on some of my photographs, but it is not measurable. At the place *C* a line is due whose wave-length is within 0.4 Å of the line 3841; it cannot be seen separately.

FORMULAE FOR FIRST SUBORDINATE SERIES

In calculating the equation of this series, there is a choice of lines to be used. I have taken the following wave-numbers: 17180.0; 22194.4, 24447, 25659, and 26395. These I have obtained by calculation from observed lines in the triplets as the most probable values for the line of greatest wave-length in each triplet. Unfortunately this line is missing in all but the first triplet; but, since it heads the tabulation on Rydberg's scheme, it seems to be analogous in position to the first line of the second subordinate triplets, and therefore to be the best to use in the calculations.

Kayser and Runge's formula cannot be used to represent the first subordinate series of *Ba* with very satisfactory results. Rydberg's type suits it better, and the formula runs as follows:

$$1/\lambda = 28300.2 - \frac{91015.6}{(m + .8609)^2} .$$

The errors (calc. λ − obs.) for the various lines are as follows:

0.0   0.0   −0.17   +1.2   +4.0

A better agreement is given by the formula,

$$1/\lambda = 28481 - \frac{109675}{(m+.37045)^2 - 1.655},$$

which contains three adjustable constants, the number 109675 being the universal series-constant used by Ritz. The errors with this formula are:

0.0   0.0   +0.02   −0.7   −0.5

This is entirely satisfactory. The calculated first term would be near 12 μ.

FORMULAE FOR SECOND SUBORDINATE SERIES

Kayser and Runge's type fails conspicuously with this series when the first (and most important) line is included; the same thing happens also in the case of *Ca* and *Sr*. Rydberg's is very little better. It runs as follows:

$$1/\lambda = 28466.6 - \frac{99091}{(m+.5026)^2}.$$

The errors (as above) are:

0.0   0.0   0.0   −7.5   −15. Å

The observations for the fourth line are accurate to 1 Å. These errors are therefore intolerable.

Ritz[1] has proposed two types of formulae (with three adjustable constants), neither of which fits this series as well as Rydberg's. I have made a lengthy search for any modification of any of these formulae which would suit this series better without introducing a fourth constant, but so far without success. This result is the more unexpected since Ritz's formula is quite successful with the second subordinate series of *Ca* and *Sr*, but a careful review of the observations and calculations shows no other alternative. I am therefore reluctantly driven to make use of a four-constant formula. Of the many possible types, I have calculated out the following one:

$$1/\lambda = 28062 - \frac{73392.7}{(m+.9027)^2 + 1.1403}.$$

This gives practically perfect agreement for all five lines; four of them were, of course, used for the calculation of the constants.

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[1] *Annalen der Physik*, 12, 264, 1903.

The spectra of *Ca*[1] and *Sr*[2] contain groups of narrow triplets which form at least one series, and probably two. These are present in *Ba* also; Rydberg gave their correct wave-number differences, but not their positions. The more important series contains the following lines, and is of the first subordinate type, i. e., complex:

TABLE III

NARROW TRIPLETS SERIES

$1/\lambda$	ν	$1/\lambda$	ν	$1/\lambda$
25018.6 25033.1	381.7	25386.0 25400.3	182.1	25568.1
29227.5	374.6	29602.1	178.0	29780.1
31017.2	376.5	31393.7		
32047.6(?)				

Most of these lines are diffuse and faint, and I do not think that the observations are complete enough at this time to make it worth while to fit a formula to this series. I hope to be able to report on this at a later date, as also upon the series of pairs in this spectrum, whose existence was first shown by observations on the Zeeman effect.

It is a pleasure to record my indebtedness to Mr. J. H. Morecroft, now of the Pratt Institute, Brooklyn, for the very great assistance which he gave me, while a student in this university, in the laborious task of plotting this spectrum, and searching for regularities in it.

SYRACUSE UNIVERSITY
June 1908

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[1] *Astrophysical Journal*, 21, 195, 1905.

[2] *Ibid.*, 21, 81, 1905.

THE SPECTRUM OF COMET *d* 1907 (DANIEL)

By W. W. CAMPBELL

The spectrum of Comet *d* 1907 was observed on several mornings between July 14 and September 8, 1907, with the one-prism spectroscope described in *Lick Observatory Bulletin* No. 8 and illustrated in *Bulletin* No. 62, as attached to the 36-inch refractor.

On July 14 the spectrum was observed visually. The carbon bands whose edges are at λ 4737, λ 5165, and λ 5635 were present in their usual relative intensities, but the continuous spectrum of the nucleus and coma was relatively strong. The nucleus, conspicuous with low power, was so large and weak under the higher magnification of the 36-inch refractor, that it was not worth while exposing for the photographic spectrum.

By August 9 the character of the visual spectrum had changed considerably. The continuous spectrum of the nucleus remained strong. The spectrum of the coma consisted principally of the three carbon bands, that at λ 5165 showing two or three maxima corresponding to the heads of component flutings, but the continuous spectrum between the bands was faint. The bands seemed to cross the nucleus without perceptible strengthening at the nucleus. The bands were followed out into the tail for about 1°, but they grew fainter with increased distance from the nucleus, and fainter relatively to the continuous spectrum. Beyond 1° the spectrum of the tail was faint, and it was not certain that the bands were present, though the continuous spectrum could still be seen. Dr. Albrecht took part in the observations on this night, and his results were in harmony with mine.

As the comet approached perihelion, on September 4, the bright bands appeared to develop in relatively greater strength.

Exposures for spectrograms were made on nine mornings. One of two hours on July 28 and another of sixty-five minutes on August 28 recorded the strongest lines but faintly. An exposure of two hours with the three-prism Mills Spectrograph, made in the hope of recording the brighter lines of the blue carbon band, as a basis for determining their wave-lengths very accurately, did not succeed; and an exposure of ninety minutes on August 15 with the one-prism instrument, using a wide slit directed upon the tail at a point $\frac{3}{4}$° from the nucleus, likewise gave no record. The other five exposures were very successful. The table below contains the wave-lengths of bright lines obtained from the five plates, as well as Kayser and Runge's wave-lengths of prominent lines in the carbon and cyanogen spectra,[1] and the wave-lengths of lines observed by me in Comets *c* 1893[2] and *b* 1894[3] and by Wright in Comet *a* 1899.[4] The first line of headings in the table gives the astronomical date of observation, the second line the exposure time, and the third the name of the observer who measured the plate. The spectrogram of August 22, reproduced in an enlarged form in the accompanying Plate XV, was purposely made without comparison spectrum in order that a very long slit might be used. To obtain wave-lengths for the lines on this plate it was necessary to assume the positions of the comet bright lines at λ 3871.5, λ 4737.2, and λ 5165.3, which are printed in italics in the table, and of the comet dark lines at λ 4101.89 ($H\delta$) and λ 4383.72 (*Fe*). The spectrogram of August 16 is on a Cramer's isochromatic plate, which accounts for the greater extension in the yellow. This spectrogram is also reproduced, with iron comparison spectrum.

Of the sixty-one bright lines catalogued in the table, a few are possibly unreliable, for the reason that they are involved with the comet's continuous and dark-line spectrum as a background, and one cannot always determine whether a certain appearance is due to a bright line or to a continuous spectrum between dark lines. In such cases the interpretations made by two observers will easily and unavoidably differ, as the table illustrates; but it appears wise to include all lines measured by each observer. They will be of interest and probable value in connection with similar observations in the future.

The observations have been corrected for the relative orbital

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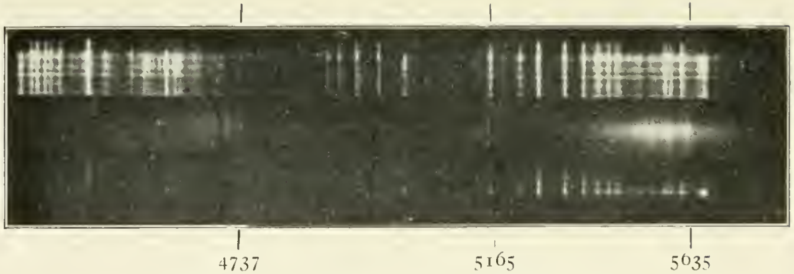
[1] *Anhang zu Abhandlungen der K. Akad. der Wiss.*, Berlin, 1889.

[2] *Astronomy and Astrophysics*, **12**, 652, 1893.

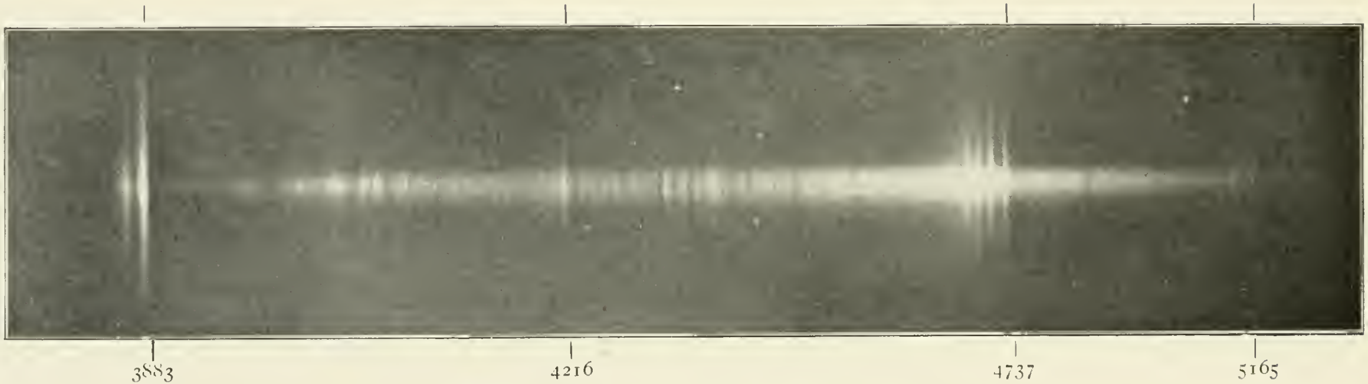
[3] *Astronomical Journal*, **14**, 111, 1894.

[4] *Astrophysical Journal*, **10**, 174, 1899.

PLATE XV



Spectrum of Comet *d* 1907 on August 16, 1907



Spectrum of Comet *d* 1907 on August 22, 1907

motions of the comet and earth. The motions relative to the sun and earth at the times of observation were:

	Comet–Sun	Comet–Earth
1907 August 10	−28 km	+14 km
August 13	−27	+19
August 16	−25	+23
August 22	−20	+29
September 8	+10	+36

In forming the mean values of wave-lengths each measure was treated as one observation: in observations of this kind, personal errors of interpretation as to the point to be measured are larger than plate errors.

There can be no doubt that the second, third, fourth, and fifth bands of the arc spectrum of carbon and the second and third bands of cyanogen are represented in the comet. In fact, they correspond very nearly to the whole of the comet's photographic bright-line radiations. There are no identifications of other elements or compounds. In particular, no trace of hydrogen bright lines could be seen, unless the very faint line at λ 3890 measured by one observer on one plate is $H\zeta$, which is improbable.

A Plücker tube spectrum of cyanogen, obtained for comparison with the same instrument, recorded a large number of strong bands throughout the spectrum, but those beginning at λ 3872 and λ 3884 are much the faintest bands within several hundred Ångström units of their positions. There appear to be no other points of resemblance or coincidence between the comet spectrum and this tube spectrum.

A spark spectrum of carbon was obtained for the same purpose. Subtracting the lines of iron, which element appears to be present as an impurity, nearly all the light falls in the third cyanogen band, beginning at λ 3884. The second cyanogen band is also recorded, but not nearly so strongly as the third. There are apparently no other points of resemblance to the comet spectrum. The measured wave-lengths obtained from the one-prism carbon spark, and Kayser and Runge's carbon arc results, are:

Carbon Spark	K. and R. Arc
3850.96	
54.66	3855.06
61.94	61.86
71.60	71.54
83.63	83.55
4152.36	4152.88
58.05	58.17
68.16	67.77
81.27	80.98
97.38	97.24
4216.36	4216.12

It is well known[1] that one cannot determine accurately the position of the edge of an unsymmetrical band, such as those here dealt with. The intensities of the individual lines composing the band, the width of the slit used, the exposure-time, etc., all affect the apparent position of the edge. Granted the monochromatic character of the lines making up the band's edge, the observer's best practice is to set the micrometer wire at a distance within the edge equal to one-half the width of the image of a neighboring comparison line whose intensity is estimated to equal the intensity of the edge of the band. A minor source of difficulty still remains, in that a symmetrical line is compared with one edge of a wide band, and slight error is scarcely avoidable.

The band at $\lambda\lambda$ 3884–3872 produced by the carbon spark and by the *CN* tube do not reproduce at all closely the relative intensities within the comet band. It is well to recall that a hydrogen tube used by Wright in studying the spectrum of Comet *a* 1899[2] gave not only the hydrogen lines but also the bands of cyanogen at λ 3884 and λ 3872 apparently exactly as they appeared in the spectra of that and all the other comets showing these bands on our spectrograms.

The reproductions of the spectrograms dated August 16 and August 22, 1907, are fairly satisfactory, though considerable detail is lost, especially in the region λ 3884–λ 3855, and the relative intensities are altered here and there. The index lines below and above are displaced in a few cases, apparently because the engraver, distant in the eastern part of the country, was not able to work more accurately to my lines on the proof sheet.

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[1] See Kayser's article in *Astronomy and Astrophysics*, **13**, 367, 1894.

[2] *Astrophysical Journal*, **10**, 174, 1899.

The continuous and dark-line spectra are shown on all the plates measured, but especially well on that of August 22. In the latter case the slit extended far on either side of the comet's nucleus, and there is no possibility that the sky spectrum of dawn exerted any influence on the result. For the spectrograms of August 10 and September 8 the continuous and dark-line spectra are strongly recorded also, but the slit on both occasions was relatively short, to permit the impressing of iron comparison spectra, and there is a doubt as to whether the sky spectrum combined with the comet spectrum and to what extent.

The continuous and dark-line spectrum of the nucleus of the reproduced plate of August 22 appears to be a duplicate of the solar or Fraunhofer spectrum, if we make allowance for the superimposed bright-line spectrum, though I strongly suspect the maximum of continuous spectrum to be displaced toward the red. However, the carbon band at λ 4737, lying near the usual maximum, complicates the question. The long bright lines cross the spectrum of the nucleus with less intensification at the nucleus than the half-tone seems to show: as if they were due almost wholly to coma radiations, the nucleus contributing to them but feebly. Many of the short bright lines, however, seem not to extend beyond the nucleus, though in many cases this may be due largely to their faintness.

The nucleus of the comet is evidently shining almost entirely by virtue of sunlight reflected by the materials composing it. Several short bright lines observed are evidence of considerable weight that there are some bright-line radiations from the nucleus. It is not impossible that a great many short lines are lost to view in the strong continuous spectrum.

The coma is evidently shining very largely by inherent light, though the faint continuous spectrum observed visually but not showing on the spectrogram would perhaps contribute appreciably to the ordinary integrated photograph of the comet.

The spectroscopic observations of the tail seem to show that the inherent light, existing in large proportion near the head, decreases in proportion to reflected or diffused sunlight with increasing distance from the head.

Independent observations by Mr. Duncan and myself showed slight

BRIGHT LINES IN COMET, CARBON, AND

1907, Aug. 10 85 minutes			Aug. 13, 94 Minutes		Aug. 16 90 Min.	Aug. 22, 65 Min.	Sept. 8 30 Minutes			Descriptions
Campbell	Plummer	Duncan	Campbell	Duncan	Campbell	Campbell	Campbell	Plummer	Duncan	
						3854.8				very faint, poorly defined
						62.4				poorly defined
3867.0						68.2				very bright, long { clearly
70.1			3870.			*3871.5*				very bright, long } resolved
74.1	3873.5					74.6				well defined
76.9						77.3				bright, not well defined
79.7			79.5	80.1	3879.1	80.5	3879.3			brightest lines on plate, long, clearly double
82.2	81.8	82.6	81.9	82.4	82.0	82.5	82.8	3882.5	82.0	brightest lines on plate, long, clearly double
	89.5									not full length of slit
						3991	3988.4			bright, short, poorly defined
						4003	4003.5	4003.5		bright, short, poorly defined
4013.9										bright, short, broad
20.2						20.4	19.3			bright, short, broad
39.4			38.8			39	38.9			bright, short, broad
42.6	42.4		42.1			44	43.0			bright, short, broad
51.0			49.9	51.5		51	50.9			bright, close double
	52.7		53.0			53				bright, close double
						65.3	65.3			fairly bright
68.1						68.9	69.5			fairly bright
74.2	74.2					73.7	{ 73.0 { { 74.9 }			bright, close double?
								4165.8		doubtful
								69.2		broad
								79.6		distinct
								85.1		clear
								89.6		clear
							4193.2	93.1		fairly bright, well defined
4214.5	14.6		14.3			14.	15.0	15.2		bright, broad, long
								4277.9		broad, bright, but uncertain as to character
								92.2		seems distinct
								97.3		very doubtful
	4304.1									faint
4313.7	14.5		13.5			13.9	13.4			faint
16.6							16.2			faint
								4335.3		very doubtful
								49.8		very doubtful
64.1	64.7		64.2			64.0	65.0	64.8		bright, rather long
71.0						70.6	71.9	71.8		not very bright
80.7	79.8					80.2	81.5	81.2		not very bright
							97.3	97.5		not very bright
								4402.3		bounded by absorption lines
						4411.7	12.4	12.6		not very bright
								19.2		bounded by absorption lines
								39.6		bounded by absorption lines
								52.1		bounded by absorption lines
								86.0		doubtful, diffused
								4537.4		sharp edge on side of smaller wave-length
								4588.9		faint, effect of contrast?
				71.1			4670.2	4670.8		bright
4677.8	78.2	77.7	77.6	78.0		78.0	76.3	77.1	77.6	very bright, well defined
84.4	83.5	84.4	84.4	84.9		84.7	84.0	84.1	84.5	very bright, well defined
96.7	96.7	96.3	96.6	97.1	98.3	97.6	96.9	96.7	97.2	very bright, well defined
							4705.0			faint
4714.7	15.1	14.7	14.4	14.6	16.0	15.3	14.4	14.5	14.2	very bright, well defined
							19.7			faint
							25.1			faint
36.2	36.5	36.2	36.3	36.2	37.8	*4737.2*	36.8	36.2	36.5	very bright, well defined
						5130				very faint
5165.7					65.4	*5165.3*	64.2	63.5		bright, well defined
					5539.5					very bright, well defined
					83.7					very bright, well defined
					5634.1					very bright, well defined

CYANOGEN SPECTRA

No. of Values and Mean Value	Kayser and Runge's Arc Spectra		Bright Lines Observed in Spectrum of Comet *b* 1893	In Comet *b* 1894	In Comet *a* 1899
1, 3855	3855.06	4th edge, 3d Cyanogen Band			
1, 3862	3861.86	3d edge, 3d Cyanogen Band			
2, 3867.6					
3, 3870.5	3871.54	2d edge, 3d Cyanogen Band	3870.0	3869.4	3870
3, 3874.1	3874.32	strong line, 3d Cyanogen Band			
2, 3877.1					
6, 3879.7	3879.62	mean of 6 strong lines, 3d CN Band			
10, 3882.3	3883.55	1st edge, 3d Cyanogen Band	3881.2	3879.5	3880
1, 3890					
2, 3990			3988	3987	3987
3, 4003					
1, 4014			4011	4015.7	4014
3, 4020.0			4019.2		4019
4, 4039.0				4040.9	
5, 4042.8			4043.1		4042
5, 4050.9	4051.00	strong line, 2d CN Band		4050.5	
3, 4052.9	4053.35	strong line, 2d CN Band	4052.3		4052
2, 4065.3					
3, 4068.8	4069.33	strong line, 2d CN Band	4069	4070.7	
4, 4074.0	4073.69	strong line, 2d CN Band	4075		4074
1, 4166	4165.34	mean of 2 strong lines, 2d CN Band			
1, 4169	4167.77	4th edge, 2d Cyanogen Band			
1, 4180	4180.98	3d edge, 2d Cyanogen Band			
1, 4185	4185.44	mean of 2 strong lines, 2d CN Band			
1, 4190	4189.63	mean of 3 strong lines, 2d CN Band			
2, 4193.2	4193.03	strong line, 2d Cyanogen Band	4196.2	4196.7	
6, 4214.6	4216.12	1st edge, 2d Cyanogen Band	4214.2	4213.8	421–
1, 4278					
1, 4292					
1, 4297			4298.4	4299.1	
1, 4304					
5, 4313.8			4313.0	4312.6	4313
2, 4316.4					
1, 4335			4334.8	4333.3	
1, 4350			4350	4350.6	
6, 4364.5	4365.01	3d edge, 5th Carbon Band	4366.2	4366.6	
4, 4371.3	4371.31	2d edge, 5th Carbon Band		broad band	4369
5, 4380.7	4381.93	1st edge, 5th Carbon Band		broad band	
2, 4397.5					
1, 4402					
3, 4412.2					
1, 4419					
1, 4440					
1, 4452					
1, 4486					
1, 4537					
1, 4589					
3, 4670.7					
9, 4677.6			4675.1		
9, 4684.3	4684.94	4th edge, 4th Carbon Band	4683.2	4681	
10, 4697.0	4697.57	3d edge, 4th Carbon Band	4697.0	4697.4	
1, 4705					
10, 4714.9	4715.31	2d edge, 4th Carbon Band	4716.0	4716.0	472–
1, 4720					
1, 4725					
10, 4736.6	4737.18	1st edge, 4th Carbon Band	4736.2	4735.8	
1, 5130	5129.36	2d edge, 3d Carbon Band	5126	5124	
5, 5164.8	5165.30	1st edge, 3d Carbon Band	5162.6	5163.5	
1, 5539.5	5540.86	3d edge, 2d Carbon Band			
1, 5583.7	5585.50	2d edge, 2d Carbon Band	5580		
1, 5634.1	5635.43	1st edge, 2d Carbon Band	5633	563–	

polarization effects in the parts of the tail near the head and in the coma, prior to August 14, but none after that date; and none were observed at any time in the light of the nucleus. The proportion of inherent to foreign light evidently increased so that by August 14 the comet's own radiations were strong enough to mask any polarization produced in diffused sunlight by the coma and tail. The particles composing the nucleus and that part of the tail yielding a continuous spectrum were evidently large in comparison with the wave-length of light. To move away from the sun in obedience to radiation-pressure, they would have to be smaller than certain limiting sizes. The angle at the comet between sun and earth was favorable for polarization effects, being about 80° for the August observations.

LICK OBSERVATORY

ON A NEW LAW OF SERIES SPECTRA

By W. RITZ

This communication is intended to show how we may derive from the known spectral series of an element, new series which represent accurately, without the inclusion of any new constant, nearly all of the series and lines recently discovered by Lenard, Konen, Hagenbach, Saunders, Moll, Ramage, and Bergmann. The new principle of combination also finds application to other spectra, particularly to helium and the earth alkalies. Closer relationships to the atomic weight than have been known hitherto are also furnished.

In its most convenient form, the series formula proposed by me reads:[1]

$$\nu = A - \frac{N}{[m+\alpha+\beta(A-\nu)]^2}, \qquad (1)$$

where ν is the wave-number referred to a vacuum, N is a universal constant, m the numeral, and A the limit of the series; α and β are constants. For small values of m, ν may become negative, which must be taken into account in the term $\beta(A-\nu)$. The constants α and β characterize the course of the series: they are identical for two series with constant differences.

We also have approximately

$$\nu = A - \frac{N}{\left[m+\alpha+\dfrac{\beta N}{m^2}\right]^2}. \qquad (2)$$

We use for abbreviation

$$m, \alpha, \beta = \frac{N}{[m+\alpha+\beta(A-\nu)]^2}. \qquad (3)$$

Let the constants α and β have the values d and δ for the pairs of the first subordinate series for instance ("diffuse series" according to Rydberg's notation); for the second subordinate series (Rydberg's "sharp series") let the values be s, σ; for the principal series, let

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[1] *Annalen der Physik*, **12**, 264, 1903. Inaugural Dissertation.

the values be p_1, π_1, and p_2, π_2; for the alkalies $\pi_1 = \pi_2$ very approximately.[1]

If the first subordinate series has a satellite, a different set of values, d', δ', applies to the second principal line, where again $\delta = \delta'$, approximately.

The statement of three series may now be written (*loc. cit.*, p. 291): Principal series:

$$\pm\nu = (1.5, s, \sigma) - (m, p_i, \pi_i)\ , \qquad i = 1, 2;\ m = 2, 3, 4 \ldots\ldots, p_1 > p_2 \,.$$

Second subordinate series:

$$\pm\nu = (2, p_i, \pi_i) - (m, s, \sigma)\ , \qquad i = 1, 2;\ m = 1.5,\ 2.5,\ 3.5 \ldots\ldots$$

First subordinate series:

$$\pm\nu = \begin{cases} (2, p_i, \pi_i) - (m, d, \delta)\ , & m = 3, 4, 5 \ldots\ldots \text{(first principal line and satellite).} \\ (2, p_2, \pi_2) - (m, d', \delta')\ , & m = 3, 4, 5 \ldots\ldots \text{(second principal line).} \end{cases}$$

The constant separation of the doublet is $\nu_1 = (2, p_1, \pi_1) - (2, p_2, \pi_2)$. On the basis of the observed data now available, the following points may be shown:[2]

1. In the equation of a principal series, if we replace 1.5 by the larger numbers 2.5, 3.5, ... ; and in the equation of a subordinate series, if we replace 2 by the larger numbers 3, 4, 5, ... , new lines will result which have been observed in many cases. This was already suspected by Rydberg.

2. For every symbol (m, α, β) there exists a minimum number m (namely, 3 for the first subordinate series; 1.5 for the second subordinate series, according to the notation of my dissertation already cited), which is a fundamental number; if we assign still smaller values to m, we should expect a stronger line, but in practice this line has not been observed. I have already shown[3] that in no spectrum does an actual line correspond to the numeral $n = 2$ of the first

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[1] *Loc. cit.*, p. 291.

[2] The reader will find further particulars in a paper to appear presently in the *Physikalische Zeitschrift.*

[3] *Annalen der Physik*, **25**, 660, 1908; *Physikalische Zeitschrift*, **9**, 244, 1908

subordinate series, in so far as the observations are adequate on this point.

3. If we form from these symbols the new combination $(1.5, s, \sigma)-(3, d, \delta)$ we obtain new lines which have been observed in case of *He, K, Rb,* but which are lacking in *Na* and *Li* thus far; for the earth alkalies they fall in the infra-red. The observed value for *He* is $\nu=26244.86$, the observed value is 26244.78.

4. In case of *Li* and *Na,* there has been also observed the combination $(2, p_1\pi_1)-(m, p_1\pi_1)$; $(2, p_2\pi_2)-(m, p_2\pi_2)$; $m=3, 4 \ldots$.

5. If we form $(3, d, \delta)-(m, p_1-p_2, \pi_1-\pi_2)$; $m=4, 5, \ldots$ then we get the infra-red series found by Bergmann[1] for *K, Rb, Cs,* and the corresponding lines for *Li, Na, He,* which were unknown.

For *Rb* and *Cs,* the first subordinate series has a satellite, so that we have further a second series $(3, d', \delta')-(m, p_1-p_2, \pi_1-\pi_2)$, which runs along in the neighborhood of the first, and has a constant difference with respect to this, as was observed by Bergmann, and even earlier by Saunders in case of *Cs,* while for *Rb* the lines could not be separated. The fundamental number for this newly formed symbol $(m, p_1-p_2, \pi_1-\pi_2)$ is $m=4$.

6. The following combinations also exist:

$$(2, p_i, \pi_i)-(m, p_1-p_2, \pi_1-\pi_2)\,, \quad i=1, 2;\ m=4, 5, \ldots$$

The pair shading toward the violet of *Na,* the corresponding pair of *Cu,* and the series of lines which have been found in *Li* and *Na,* by Lenard, Konen, and Hagenbach, belong here.

$$(4, p_1-p_2, \pi_1-\pi_2)-(m, p_1-p_2, \pi_1-\pi_2)\,.$$

7. Extended investigations, such as exist for the alkalies, are lacking for the earth-alkalies in the infra-red region; and the principal series have not been observed, showing that the test of the principle of combination, in the sense hitherto used, cannot be made at present. The following circumstances, however, indicate that it is also valid here: in the first subordinate series of the series of triplets, with two satellites, we have to introduce the new symbols (m, p_3, π_3), (m, d'', δ'') with $p_1>p_2>p_3$. In the first approximation we may neglect

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[1] Inaugural Dissertation, Jena, 1907; also C. Runge, *Physikalische Zeitschrift,* 9, 1, 1908.

$\pi_1-\pi_2$, $\pi_2-\pi_3$, and compute p_1-p_2, p_2-p_3, from the limits of the subordinate series, in spite of the fact that the principal series have not been observed; p_1-p_2 will be about twice as large as p_2-p_3, and the two differences of the vibration number (designated by Rydberg as ν_1 and ν_2) are

$$\nu_1=(2,\,p_2,\,\pi_2)-(2,\,p_1,\,\pi_1)\ ;\qquad \nu_2=(2,\,p_3,\,\pi_3)-(2,\,p_2,\,\pi_2)\ .$$

There frequently occur double lines, with the distance ν_1, and triplets with the distance ν_1, ν_2, outside of the series. This is to be expected on the principle of combination only, and only when $(2,\,p_i,\,\pi_i)$ are associated with any quantity $(m,\,\alpha,\,\beta)$. These doublets and triplets must therefore belong to series which end at the same point $(2,\,p_i,\,\pi_i)$ as the subordinate series already known, but of which only a few terms of sufficient intensity are to be perceived.

It was further possible to find the equation of the second subordinate series for the strong ultra-violet pairs for *Ca*, *Sr*, *Ba*, for which the difference of the vibration-numbers ν' is to be twice as large as ν_1, and from the elements of these double lines to form the corresponding differences of the constants p, on the assumption that $\pi_1-\pi_2=0$. The distance differs from that of the series of triplets by only about 15 per cent.; in the same exact computation, the two quantities would probably become equal to each other, which would correspond to the principle of combination.

Finally, subordinate series of close triplets have recently been found for *Ca* and *Sr*, by Fowler and by Saunders, from the limits of which again the differences $p'_1-p'_2$, $p'_2-p'_3$, can be formed. Within the limits of accuracy of these, it appears that they are the same as those computed from the satellites and principal lines of the first subordinate series $d-d'$, $d'-d''$, so that a new combination exists here.

It further appears of advantage, in respect to the relations with the atomic weight, to introduce the constants of the formula in place of the wave-numbers, in spite of the fact that this can only be regarded as an approximation. It is well known, for instance, that the quotient of ν_1 and the square of the atomic weight μ does not vary much within a group of chemically related elements; but on the contrary it varies greatly from group to group, from 31.6 for *Cs*, to 187.0 for *Tl.* We introduce $\frac{p_2-p_1}{\mu^2}$ in place of $\frac{\nu_1}{\mu^2}$ and the variation becomes much less.

The discrepancies which still remain are probably due in part to the incompleteness of the series formulae, but particularly to the neglect of $\pi_1-\pi_2$, which certainly is not admissible in the case of *Al, In,* and *Tl.* A knowledge of the principal series of these elements would enable us to decide about this.

Element*	*Na*	*K*	*Rb*	*Cs*	*Cu*	*Ag*	*Mg*	*Ca*
$\frac{\nu_1 103}{\mu^2}$	32.3	37.8	32.3	31.6	61.8	79.0	68.8	66.1
$\frac{p_2-p_1}{\mu^2}10$....	14.2	18.9	18.0	18.6	18.6	24.2	14.6	17.7

Element*	*Sr*	*Zn*	*Cd*	*Hg*	*Al*	*In*	*Tl*	*He*
$\frac{\nu_1 103}{\mu^2}$	51.5	91.0	93.2	115.4	152.8	172.1	187.0	63.8
$\frac{p_2-p_1}{\mu^2}10$....	15.7	17.2	18.6	22.3	24.8	29.2	32.7	20.4

* According to the summary by Rydberg, *Rapports du Congrès de Physique*, Paris, 1900. Tome 2.

It is known that with increasing atomic weight the series fall off with increasing rapidity, so that only those lines are observed which correspond to the lowest numbers of the order. At the same time the number of the different series increases (even *Mg* shows series of double lines and of simple lines in addition to the series of triplets) and the number of combinations increases. Thus we finally reach a spectrum in which we may perceive a large number of characteristic constant differences, but no series. It seems to me very probable that the so-called spectra of the second class which exhibit this behavior are spectra with very many combinations and with very slightly developed series.

The computation of a quantity (m, a, β) assumes a knowledge of the elements of a series in the formula of which it enters. This element may be determined with great accuracy, except when only a few diffuse lines are observed; it is also somewhat independent of the outstanding uncertainty as to the exact form of the equation of the series. In the cases cited under (1), (3), (4), we have indeed to compute exclusively differences and sums of observed wave-numbers; the accuracy is naturally still greater here. But on the other hand the constants entering into the symbol $(m, p_1-p_2, \pi_1-\pi_2)$ may be varied by 20 per cent. without making the difference between computation and observation much worse. On account of their smallness the influence of the constants p_1-p_2, $\pi_1-\pi_2$, is relatively slight compared to that of m, and the series run along nearly parallel with Balmer's series, particularly for *Li*, *Na*, and *He;* for greater atomic weight the observations are hitherto too inaccurate to give us any certainty on this point.

In a paper which recently appeared[1] I have shown that we may cite systems of the simplest sort of which the energy is purely electromagnetic and which observe Balmer's formula, the laws of series and the analogous Zeeman effect, etc. The vibration

$$v=N\left[\frac{1}{4}-\frac{1}{m^2}\right]$$

is produced by the magnetic field of $m-2$ elementary magnets turned toward each other, which are identical among themselves: in addition to this magnetic series the electron is subject to only rigid combinations. Similar facts hold good for other spectra. Higher numbers of the order thus correspond in a certain degree with higher magnetic polymerizations, which constantly become less stable, so that the lines become broader with an increasing number of the order, and also become constantly weaker. Violent motions, such as occur in an electric spark, are also unfavorable to stability, whence the series in the spark cease at lower numbers of the order than in the arc.

The magnetic field in an atom may be regarded in all spectra as produced by two poles of opposite sign, which separately may occupy different positions in the atom. In case of hydrogen, these points lie at equal distances on a straight line. It would appear that we may more generally state the principle that the simple lines refer to or depend upon the positions of these poles in the atom. In (m, a, β) $-(n, a', \beta')$ each of the terms represents the influence of one pole;

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[1] "Magnetische Atomfelder und Serienspektren," *Annalen der Physik*, 25, 660, 1908.

and, as we have shown before, the possible positions of the separate poles permit the most varied combinations of the poles in pairs.

As to a certain minimum prescribed in the number of the order *m*—which occurs in the case of no known processes of vibration—this mode of representation only affirms that the magnet poles are held by the structure of the atom at a certain minimum distance from the electron vibrating within an atom, an idea which is quite plausible.

Göttingen
June 1908

THE PASADENA LABORATORY OF THE MOUNT WILSON SOLAR OBSERVATORY[1]

By GEORGE E. HALE

The spectroscopic laboratory erected in 1905 on Mount Wilson was described in *Contributions from the Solar Observatory*, No. 10.[2] As stated in that paper, our investigations of sun-spot spectra made it necessary to supplement the equipment provided on Mount Wilson with a large electric furnace, which was installed in the Pasadena instrument shop. As the further development of our sun-spot work demanded the use of a more perfect electric furnace and as our apparatus required more current than could be economically generated on Mount Wilson, it seemed advisable to take advantage of the opportunity afforded in Pasadena to obtain electrical energy, at moderate cost, from the Edison Company. Accordingly a small laboratory, adjoining our instrument shop and standing immediately in front of the Hooker Building, was erected during the winter of 1908 (Plate XVI).

In the Mount Wilson laboratory the various light-sources are arranged on the circumference of an annular pier. A plane mirror at the center, which can be rotated about a vertical axis, reflects the rays from the light-source under examination to a concave mirror, which forms an image on the slit of a horizontal Littrow spectrograph of 18 feet (5.5 m) focal length. In the Pasadena laboratory, profiting by experience with the tower telescope,[3] a vertical Littrow spectrograph, of 30 feet (9.1 m) focal length, is mounted in a well, with waterproof brick walls, extending 30 feet below the surface of the ground. The electric furnace and other light-sources stand on separate piers, arranged in a circle about the center of the spectrograph slit. The spectrograph can be rotated about the axis of the

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 27.

[2] *Astrophysical Journal*, **24**, 61, 1906.

[3] *Contributions from the Mount Wilson Solar Observatory*, No. 23; *Astrophysical Journal*, **27**, 204, 1908.

PLATE XVI

The Pasadena Laboratory

PLATE XVII

Interior of the Pasadena Laboratory

collimator and light from any source is reflected into the slit by means of a plane mirror standing (at 45°) above it (Plate XVII).[1]

This arrangement determines the general plan of the laboratory (Fig. 1). The outside dimensions of the building are 32×44 feet. The walls are of brick, the floor of cement, and the ceiling of corrugated iron. The well which contains the spectrograph, 8½ feet inside diameter, is near the middle of the principal room. As the spectrograph stands eccentrically, near one side of the well, considerable space is left in the well for other instruments requiring constant temperature conditions.

Except in one particular, the 30-foot spectrograph is precisely similar to the one used with the tower telescope.[2] In addition to an 8-inch (20.3 cm) objective of 30 feet focal length, it is supplied with a 5-inch (12.7 cm) objective of 13 feet (4 m) focal length.[3] This objective, together with an adjustable grating-holder mounted in conjunction with it, can be swung out of the axis of the spectrograph when the objective of 30 feet focal length is to be employed. Thus a considerable range of dispersion, from the first-order spectrum with the 13-foot objective to the fourth-order spectrum with the 30-foot objective, is available. Both objectives can be focused from the eye-end of the instrument and the grating can be rotated from the same point. The only gratings at present available are a 5-inch Rowland plane, having 14,438 lines to the inch, kindly loaned to us by the Johns Hopkins University, and a 4-inch Michelson plane, having 500 lines to the millimeter.

The concrete floor is continued over the well, the spectrograph ring being supported on a cylinder of concrete rising from it. The temperature at the bottom of the well is so constant that exposures of any desired length can be given, without fear of displacement of the lines arising from changes in the temperature of the grating.

A small fireproof room in the laboratory contains five transformers,

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[1] The mirror support shown is a temporary one, and will be replaced later by a different apparatus, carrying also a lens, on a radial arm, to form an image of any source on the slit.

[2] *Loc. cit.*

[3] Both visual and photographic objectives of this size, formerly employed in photographing spectra with the Snow telescope, are available for use with this spectrograph.

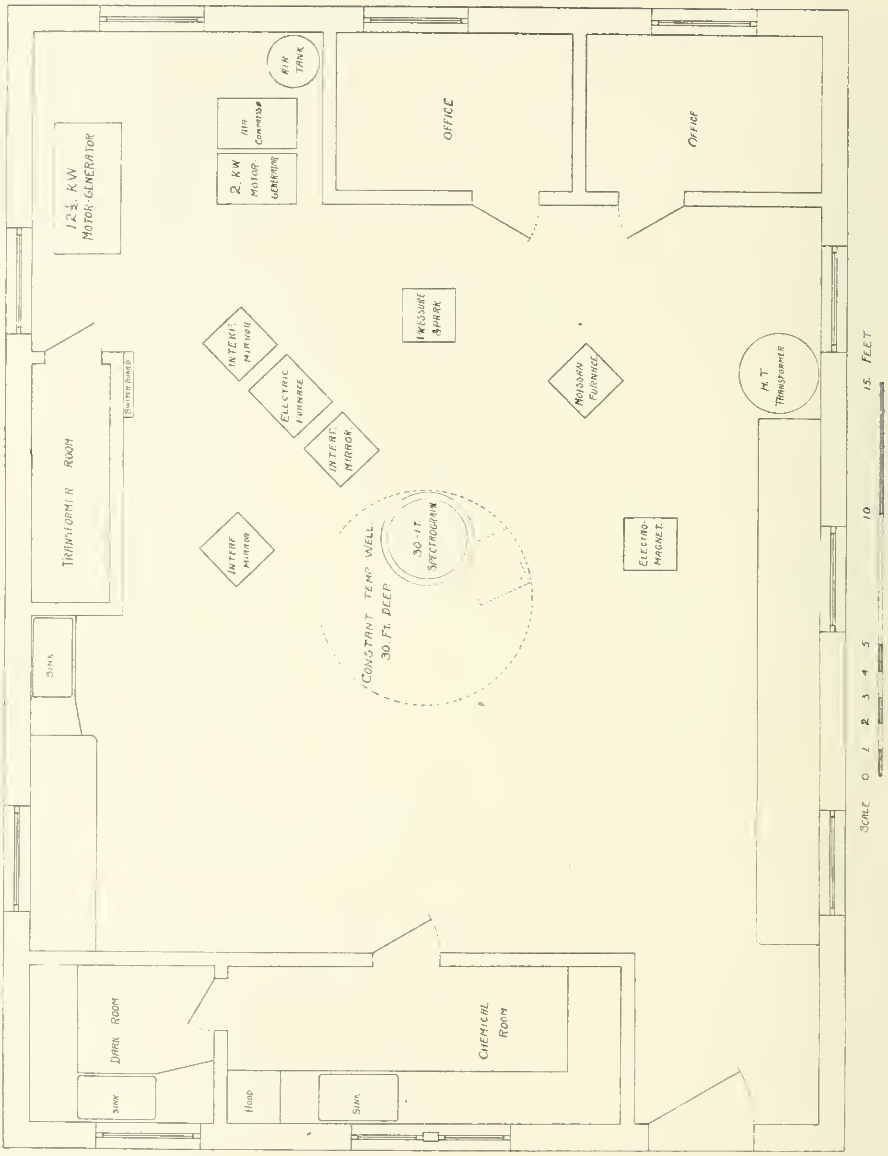

FIG. 1.—Plan of Laboratory.

connected with the 2000-volt alternating current circuit of the Edison Electric Company, as follows:

a) One low-voltage transformer, formerly used for our experiments on fused quartz, having a capacity of 50 K. W., with connections for 5, 10, 20, or 30 volts. By means of very heavy copper cables, passing through a conduit beneath the floor, this transformer supplies the resistance-tube electric furnace with current.

b) Two 30 K. W. transformers, primarily for heavy-current arc work. These may be connected either in series or parallel, giving 52 or 104 volts, with a capacity of 60 K. W., or 208 volts, with a capacity of 30 K. W.

The secondary terminals of transformers *a*) and *b*) are mounted on a slate pier in the transformer room, where they may be joined by heavy copper lugs to cables passing through conduits to the three piers designed for furnace and arc work. Thus the voltages above mentioned, ranging from 5 to 208, are available as desired at any one of these piers. The three transformers are controlled by primary oil switches, operated by cords from without the transformer room.

c) Two 15 K. W. transformers, which supply power to the machinery of the instrument and optical shops, to the motors that drive the direct-current generators in the laboratory, to the high-voltage transformer, etc.

The 5 K. W. high-voltage transformer, which stands on the opposite side of the room, is connected with highly insulated overhead wires passing across the laboratory, from which leads may be dropped to any of the piers where a spark is to be used. This transformer contains a series of step-up connections, giving 1000, 2000, 4000, 8000, 16,000, 32,000, or 64,000 volts at the secondary terminals. Within the inclosure which surrounds the transformer there are a series of self-induction coils and a large condenser, consisting of alternate plates of sheet metal and plate glass immersed in oil.

Direct current is supplied from two sources:

a) A 12½ K. W. dynamo, direct connected with a three-phase motor. Both of these machines stand on a heavy concrete pier, separated from the floor and resting on a bed of sawdust. In this way the vibration is so greatly reduced that it is not perceptible in the 30-foot spectrograph. By regulating the field of the motor the dynamo gives voltages varying from 30 to about 120. Thus the Dubois electro-magnet, which is intended for use at 64 volts, can be excited without a series rheostat. The high voltage is mainly employed for powerful electric current arcs and other similar purposes.

b) A 2 K. W. generator, direct connected with a three-phase motor, both standing on a pier separated from the floor. This gives direct-current voltages ranging from 90 to 120, and serves well for small arcs and other apparatus requiring moderate currents. The motor is also used to drive an air-compressor built by Cook of Manchester, after a design kindly prepared for us by Mr. Petavel.

Both dynamos are joined to the switchboard, where they may be connected to wires passing through conduits to two of the piers.

The principal light-sources and auxiliary instruments now employed in the laboratory are as follows:

a) A carbon or graphite tube resistance furnace (on the left of Plate XVII), inclosed in a steel cylinder capable of withstanding pressures up to 200 atmospheres. This furnace, which was designed by Dr. King, is described by him in another article.[1] The highest temperature hitherto attained in it, as measured with a Wanner pyrometer, is 3015° C. It has thus served admirably for the study of the spectra of such refractory metals as titanium and vanadium, permitting the relative intensities of their lines to be recorded at widely different temperatures. This furnace is also intended for investigations of anomalous dispersion, in conjunction with a Michelson interferometer and the 30-foot spectrograph.

b) A rotating arc in a pressure chamber, formerly used in the Mount Wilson laboratory.

c) An inclined arc electric furnace (near the middle of Plate XVII), similar in type to one used by Moissan, but modified according to designs by Dr. Olmsted so as to permit the arc to be observed in an atmosphere of hydrogen or other gas. For regulating the current a large rheostat is provided. This furnace is now used by Dr. Olmsted in his work on the fluted spectra of calcium hydride and other compounds found in the spectra of sun-spots and red stars. A Geryk

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 28.

duplex vacuum pump, driven by a small electric motor, is used with the two furnaces when low pressures are required.

d) Spark terminals, mounted between the poles of a large DuBois electro-magnet formerly used in the Mount Wilson Laboratory. This apparatus, which is shown on the right of Plate XVII, is being used for the study of the Zeeman effect in the spectra of iron, titanium, and other elements that occur in the spectra of sun-spots.

e) An ordinary electric arc, used for comparison spectra, etc.

A one-prism quartz spectrograph and a direct vision spectroscope are employed for the preliminary examination of spectra. Other apparatus used in the Mount Wilson Laboratory and described in *Contribution* No. 10 is also available. A two-mirror heliostat, mounted on the roof immediately above the 30-foot spectrograph, supplies sunlight for comparison spectra. Piers for vacuum tube apparatus and other light-sources will be erected as occasion demands.

At the west end of the building there is a small chemical laboratory and a photographic dark-room. At the east end are the offices of Dr. King, superintendent of the Physical Laboratory, and Dr. Olmsted.

A more detailed account of the instruments used in the laboratory will appear in subsequent papers.

MOUNT WILSON SOLAR OBSERVATORY
August 1908

ASTRONOMICAL AND ASTROPHYSICAL SOCIETY

The Astronomical and Astrophysical Society of America held its meeting at Hotel Victory, Put-in-Bay Island, Lake Erie, on August 25, 26, and 27, with Professor E. C. Pickering, president, in the chair.

The following papers were presented:

ASAPH HALL: "Formulas Used for the Reduction of Satellite Observations."

G. W. HOUGH: "Doolittle's Measures of the Hough Double Stars."

W. S. EICHELBERGER: "The Standard Clock of the U. S. Naval Observatory."

C. L. DOOLITTLE: "Examination of the Reflex Zenith Tube."

E. E. BARNARD: "On the Period of the Variable Star No. 33 in Messier 5, and on the Constancy of the Period."

E. D. ROE, JR.: "Achromatic and Apochromatic. Comparative Tests. Preliminary Communication."

E. E. BARNARD: "On a Quick Visual Method of Correcting for the Changes of Focus in the Large Visual Telescope when Used for Photography with a Color-Filter."

E. E. BARNARD: "On the Focal Changes in the Image of *Nova Persei* and on the Focus for Some of the Wolf-Rayet Stars."

G. C. COMSTOCK: "Approximate Ephemerides of the Fixed Stars."

E. C. PICKERING: "A New Form of Stellar Photometer."

E. C. PICKERING: "Standard Photographic Magnitudes"

FRANK SCHLESINGER: "On the Character of the Light-Variations of *u 68 Herculis*."

J. A. PARKHURST: "Light-Curve of the Variable Star *SU Cassiopeiae* from Extra-Focal Photographs." (Lantern.)

E. E. BARNARD: "On the Inequalities in the Proper Motion of the Star *Krueger 60*, Due to Orbital Motion." (Lantern.)

J. S. PLASKETT: "The Coelostat Telescope of the Dominion Observatory." (Lantern.)

J. S. PLASKETT: "Camera Objectives for Spectrographs." (Lantern.)

MRS. M. FLEMING: "A Proposed Sixth Type of Stellar Spectra."

C. D. PERRINE: "A Determination of the Solar Parallax from the Crossley Photographs of *Eros*."

W. W. CAMPBELL: "The Lick Observatory Eclipse Expedition to Flint Island."

PHILIP FOX: "Prominences on the Solar Disk." (Lantern.)

MILTON UPDEGRAFF: "The Work of the Nautical Almanac Office."

G. W. HOUGH: "On an Infinite Universe."

G. C. COMSTOCK: "The Luminosity of the Brighter Lucid Stars."

FRANK SCHLESINGER: "Photographic Determinations of Stellar Parallax with the Yerkes Refractor."

JOEL STEBBINS: "The Measurement of Starlight with a Selenium Photometer."

EDWIN B. FROST: "Spectrographic Observations."

F. H. SEARES: "Results of Photometric Investigations."

W. T. CARRIGAN: "An Investigation of Terms in the Mean Longitudes of *Mars* and the Earth, That Have the Argument, $3\,J-8\,M+4\,E''$."

W. J. HUMPHREYS: "The Temperature Gradient of the Atmosphere and an Attempt to Account for the Upper Inversion."

J. S. PLASKETT: "Effect of Increasing the Slit-width upon the Accuracy of Radial Velocity Determinations."

RAYMOND S. DUGAN: "The *Algol* System *RT Persei*."

The time and place of the next meeting will be decided later by the Council.

NOTICE

The scope of the ASTROPHYSICAL JOURNAL includes all investigations of radiant energy, whether conducted in the observatory or in the laboratory. The subjects to which special attention is given are photographic and visual observations of the heavenly bodies (other than those pertaining to "astronomy of position"); spectroscopic, photometric, bolometric, and radiometric work of all kinds; descriptions of instruments and apparatus used in such investigations; and theoretical papers bearing on any of these subjects.

Articles written in any language will be accepted for publication, but unless a wish to the contrary is expressed by the author, they will be translated into English. Tables of wave-lengths will be printed with the short wave-lengths at the top, and maps of spectra with the red end on the right unless the author requests that the reverse procedure be followed.

Accuracy in the proof is gained by having manuscripts type-written, provided the author carefully examines the sheets and eliminates any errors introduced by the stenographer. It is suggested that the author should retain a carbon or tissue copy of the manuscript, as it is generally necessary to keep the original manuscript at the editorial office until the article is printed.

All drawings should be carefully made with India ink on stiff paper, usually each on a separate sheet, on about double the scale of the engraving desired. Lettering of diagrams will be done in type around the margins of the cut where feasible. Otherwise printed letters should be put in lightly with pencil, to be later impressed with type at the editorial office, or should be pasted on the drawing where required.

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AND ASTRONOMICAL PHYSICS

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THE DISTRIBUTION OF ERUPTIVE PROMINENCES ON THE SOLAR DISK[1]

By PHILIP FOX

Spectroheliograms taken with calcium radiation using the H or K line often show especially brilliant points in the flocculi in the neighborhood of spots. These were noticed by Hale and Ellerman in their early work with the Rumford spectroheliograph and even earlier on the Kenwood spectroheliograms. On account of their brilliancy and occasional rapid change of form, and because hydrogen spectroheliograms generally had brilliant points in the same region, they were called eruptions.[2]

While I have been observing with the Rumford spectroheliograph I have given these eruptions careful attention and the evidence seems conclusive that they are the bases of eruptive prominences. Observations of their spectrum made visually and photographically show that the reversals of the H and K lines, indicative of the presence of flocculi, are here very strong and often show distortion; that the $H\epsilon$ line is always reversed and sometimes many of the metallic lines; though none, so far as my observations go, that are not seen in the spectrum of eruptive prominences. Observations on September 12, 1907, will

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[1] The essence of this paper was contained in two communications: (1) to Section A of the American Association at the Chicago meeting, January 1908, "The Detection of Eruptive Prominences on the Solar Disk;" (2) to the Astronomical and Astrophysical Society of America at Put-in-Bay, August 1908, "The Distribution of Eruptive Prominences on the Solar Disk."

[2] *Publications of the Yerkes Observatory*, 3, Part I, 18 and 22.

illustrate. There was on my photographs such a brilliant eruption in the midst of the small spots of the group then just past the central meridian in the southern hemisphere, Greenwich No. 6247 and 6252. Hurried, visual examination in the blue and violet showed a number of lines reversed. Besides H and K there were $H\delta$, $H\epsilon$, $H\zeta$, iron lines at λ 4046 and 4005, strontium at λ 4078, calcium at λ 4227, and aluminum at λ 3961 and 3944—all prominence lines. A photograph of the limited portion of the spectrum admitted to the plate through the opened second slit of the spectroheliograph, about 65 Ångströms in the region of the H and K lines, shows the reversal of the two aluminum lines mentioned above. Young in discussing spot spectra makes the following statement:[1] "At times the spectrum of a spot gives evidence of violent motion in the outlying gases by distortion and displacement of the lines. When the phenomenon occurs, it is more usually at points near the outer edge of the penumbra." He was surely observing the phenomena under discussion here. Again he says: "In a few instances the gaseous eruptions in the neighborhood of a spot are so powerful and brilliant, that with the spectroscope, their forms can be made out on the background of the solar surface in the same way that the prominences are seen at the edge of the sun. In fact, there is probably no difference at all in the phenomena, except that only prominences of most unusual brightness can thus be detected on the solar surface." Deslandres states:

> La zone moyenne (autour de la pénombre) est le siège de mouvements notables, indiqués par l'inclinaison fréquente de la raie K_3 par rapport à la raie K_2, inclinaison qui, parfois, a pu être expliquée par un mouvement tourbillonnaire analogue à celui des cyclones terrestres et de même sens; cette région doit être le siège des protubérances dites éruptives.[2]

A line of evidence other than deductions from observations of the spectrum is opened when we detect these eruptions near the limb. In 1905 I noted that:[3] "In nearly all cases where these eruptions could be traced to the limb the prominence plate revealed a prominence hovering over the (eruptive) flocculus." Since then the instances of detected coincidence have been multiplied. Perhaps the most beauti-

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[1] Young, *The Sun* (rev. ed., 1904), p. 135.

[2] *Comptes Rendus*, **141**, 382, 1905.

[3] *Astrophysical Journal*, **21**, 354, 1905.

PLATE XVIII

S

E

W

FIG. 1.—COMPOSITE OF CALCIUM PROMINENCE AND DISK PLATES OF AUGUST 14, 1907. TWOFOLD ENLARGEMENT

E

W

S

FIG. 2.—CALCIUM PLATE OF AUGUST 4, 1908, SHOWING ERUPTION PRECEDING THE NEW SPOT. ORIGINAL SIZE

ful illustration found on our photographs is seen on plates obtained August 14, 1907. The flocculi plates showed a brilliant ridge in the cloud of calcium vapor about the group of spots just rounding the east limb of the sun at position angle 132°, Greenwich No. 6236. This was particularly strong on a plate at 3^h 50^m G.M.T. The prominence plate at 4^h 17^m, though badly fogged, showed the associated prominence. A second plate at 5^h 36^m was of better quality. Fig. 1 of Plate XVIII is a composite of the disk exposure at 3^h 50^m and the prominence plate at 5^h 36^m. The prominence bears a strong resemblance to the one observed by Young[1] on October 5, 1871. Other striking illustrations of this coincidence might have been made with plates of September 13, 1907, July 14, 1908, July 25, 1908, July 31, 1908, etc.

The spectroheliograms, then, show the bases of the eruptive prominences and provide a means for studying their distribution on the disk. During the present year at free moments I have been engaged in making a careful examination of all the Rumford spectroheliograms, recording in ledger form all phenomena of interest, noting the location of dark flocculi, eruptions, prominences at the limb, etc. This was undertaken primarily to show the distribution of the eruptive prominences on the disk. Before giving the summary of this feature of the ledger I will refer again to Young's observations and to others by Buss. Young, as quoted above, found the eruptions at the outer edge of the penumbra. Mr. Buss,[2] in summarizing observations made during the past ten years, describes spectroscopic observations of prominences on the disk similar to those of Young. He says: "These paroxysms usually take place behind the leader spot of an active group, in the intervening area between the leader and the chief follower, and must be intimately bound up with the evolutions of spot formation."

My observations are in absolute accord with the above, as this summary from my ledger shows: Spot birth is always accompanied by and generally antedated by an eruption. In the early hours of the life of the spot the eruption may partially or entirely cover the spot and often may precede it, in the direction of solar rotation. An eruption

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[1] Young, *The Sun* (rev. ed., 1904), p. 223, Fig. 71.

[2] *Journal of the British Astronomical Society*, **18**, 238 and 240, 1908.

is seldom seen preceding a mature single spot but if present will be following it at the edge of the penumbra, perhaps encroaching somewhat. If the spot is actively growing eruptions are almost certain to be found on the following edge. Eruptions accompany spots in rapid decline, being often seen at the ends of bridges. In complex spots where we often have a large leader, *a*, and a large spot, *b*, at the end of the stream the eruptions follow the preceding spot and precede the following spot. The instances of an eruption preceding the spot *a* or following the spot *b* are comparatively rare. Usually in such a group we find a great number of smaller spots between *a* and *b;* eruptions are usually seen among them.

The distribution of the eruptions about the spots and the similarity of arrangement of calcium and hydrogen eruptions is shown in Figs. 2, 3, and 4 of Plates XVIII and XIX. The exposures for Fig. 3 (calcium, H line) and Fig. 4 (hydrogen, $H\alpha$) were made on August 3, 1908, that for Fig. 2 (calcium H), on August 4. The eruptions between the leading spot and its followers of the southern group are in a well-marked chain. In this Fig. 2 shows considerable changes. More striking, however, is the advent of the new spot. Here, as is often the case, an eruption precedes the leading spot. It persisted in this position until August 6, then disappeared; only the eruption in the usual position between the spots remained. It is well also to say here that the north preceding spot was born on August 1. Mention will again be made of this spot. It and its southern companion were on the western limb on August 10, and both were actively emitting prominences. The following pair were showing similar activity on the limb on August 12 and 13.

It is natural to turn from these observations to a consideration of the relation of eruptions to the spots. I think the evidence of the Rumford spectroheliograms fairly conclusive in showing that the spot has its genesis in the eruption. The phenomenon of spot development following the appearance of an eruption is so general that it is possible upon the appearance of an isolated eruption to predict with certainty the advent of a spot. When the spot is well developed it stimulates new eruptions. The recent paper by Hale[1] depicts beautifully the vortices in the hydrogen about the spots. My $H\alpha$

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[1] *Astrophysical Journal*, 28, 100, 1908.

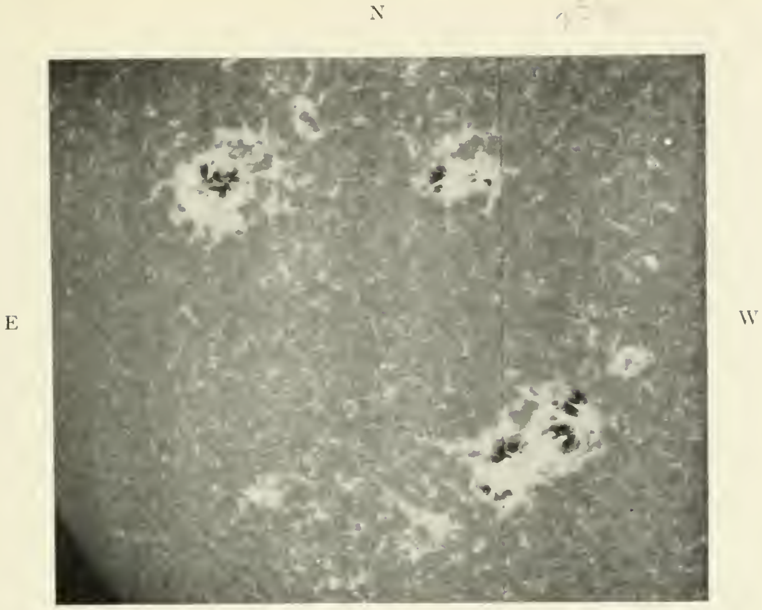

FIG. 3.—CALCIUM PLATE OF AUGUST 3, 1908, SHOWING CHAIN OF ERUPTIONS BETWEEN SPOTS OF SOUTHERN GROUP. ORIGINAL SIZE

FIG. 4.—HYDROGEN PLATE OF AUGUST 3, 1908, SHOWING LOCATION OF ERUPTIONS. ORIGINAL SIZE

FIG. 5.—HYDROGEN PLATE OF AUGUST 31, 1908, SHOWING OPPOSITELY DIRECTED VORTICES IN THE TWO HEMISPHERES. ORIGINAL SIZE

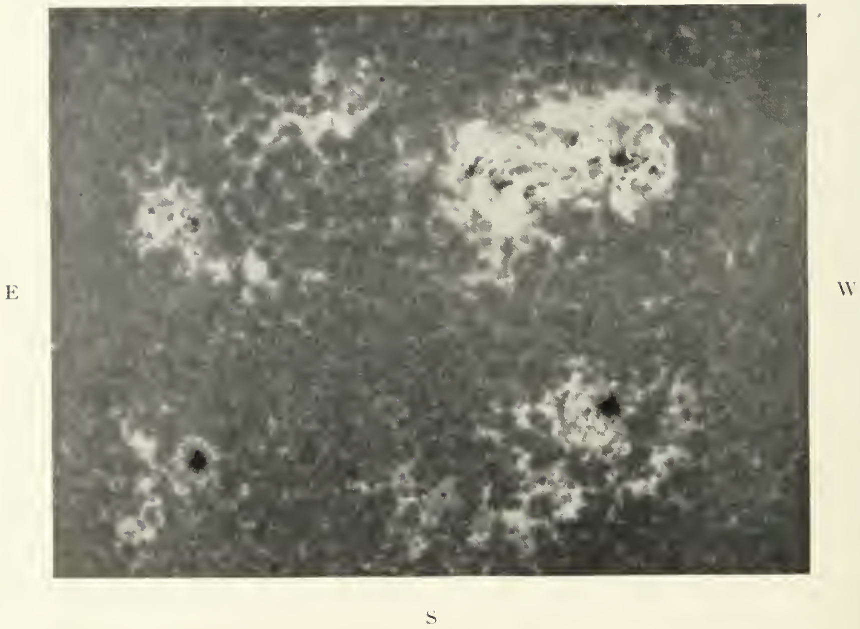

FIG. 6.—CALCIUM PLATE OF AUGUST 31, 1908. ORIGINAL SIZE

plates show that the vortices form early in the life of the spot. I obtained no *Ha* plate on September 4, the birthday of the south following spot of Fig. 2, but on an *Ha* plate of September 5, the vortex is well developed. Careful examination of this spot in calcium radiation, Fig. 2, shows the whirl on September 4. It may be stated here that many of the spots having hydrogen in well-marked vortices about them furnish also unmistakable signs of whirl of calcium vapor. The cooler matter from above seems to be drawn down into the spots. Here it may cool and contract the gases and cause an uprush of hotter, lighter gas from below, and, as suggested by Faye, the cooler, descending gas rapidly heating and expanding may also return violently to the surface. Perhaps the eruption between the spots of a well-developed group may be in part excited by the interference of the whirls.

However the eruptive prominences arise, their location between the spots and their absence in front of the leader spot and behind the follower need an explanation, and in seeking it we must consider the proper motions of the members of the group and the circulation about them.

Examination of all of the *Ha* plates and the record of earlier observed whirls in the calcium vapors results in assigning the direction as counter-clockwise in the northern hemisphere and clockwise in the southern. This is in agreement with the demands of Faye's theory. The whirl about the follower spot is seldom so well marked as about the leader. In fact, it seems questionable whether the follower ever develops a perfect whirl of its own. The direction of motion about the follower and its functions generally in the group must be carefully investigated.

Figs. 5 and 6 (Plate XX) show the details of motion about the spots of two great groups. The plates were obtained on August 31, 1908, the *Ha* plate, Fig. 5, at $5^{h}\,57^{m}.0$ G.M.T. and the calcium plate which is given for comparison at $3^{h}\,28^{m}.7$ G.M.T. The spots are those of Figs. 2, 3, and 4 on their return to the center of the disk. The small, newly born, north preceding spot of Fig. 4 now far surpasses its southern neighbor in size and activity. A few points deserve attention. The direction of motion, opposite in the two hemispheres, is apparent, though the outer part of the quiescent prominence rather masks the whirl of the southern spot. The lack of definite stucture of hydrogen flocculi in the midst of the great group is shared by nearly all large groups. The structure is almost as chaotic as in the calcium flocculi, the overlying quiescent prominences only are more clearly shown. The large quiescent prominence reaching into the northern group from the north and rear changed very slowly in form; finally it parted near the middle on September 1 and dissolved. I cannot say that it was drawn into the maelstrom. The quiescent prominence to the south of the southern spot persisted for several days. It was present in different form on August 27, and was still present on September 5, when the spot was near the western limb. I have examined the plates to see if here might not be another instance of a prominence being drawn into a spot, similar to that observed by Hale.[1] Part of it may have been and probably was drawn into the spot, but the evidence is inconclusive and on August 31 and succeeding days seems to be negative. It should be borne in mind that the prominence does not need to reach the umbra or even penumbra in order to be drawn in, but probably descends into the whirl at a considerable distance from them.

In conclusion I wish to express my thanks to Professor Slocum of Brown University for assisting me in obtaining the negatives of Fig. 1 and to Dr. Giorgio Abetti for similar help on the originals of Figs. 2 and 6.

YERKES OBSERVATORY
September 20, 1908

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[1] *Loc. cit.*

EFFECT OF INCREASING THE SLIT-WIDTH UPON THE ACCURACY OF RADIAL VELOCITY DETERMINATIONS

By J. S. PLASKETT

The result of an investigation recently undertaken at Ottawa[1] has shown that the exposure time required for star spectra in average seeing is almost inversely proportional to the slit-width until this reaches at least 0.075 mm. This is partly due to losses by diffraction at the slit-jaws but mainly to the enlargement of the star image by atmospheric disturbances, the paper above cited having shown that the effective diameter of the star image, even with the shortest exposures, is rarely less than 2″, about 0.055 mm, at the focus of the Ottawa refractor. Whatever the cause, however, the fact remains that a considerable saving in time and increase in output can be effected by an increase in slit-width. It therefore becomes a question of much interest to determine how far the accuracy of velocity determinations is affected by such increase. This can only be satisfactorily obtained from actual trial, and it is the purpose of this paper to attempt a partial solution of the problem.

There are three ways in which an increase in slit-width may lead to loss of accuracy in velocity determinations:

a) By the decrease in purity and consequent difficulty of identification of lines and determination of the blended wave-lengths.

b) By increased diffuseness and breadth of the spectral lines and consequent probable increase of errors of measurement.

c) By systematic displacements of the lines as a whole, with consequent error in the velocity, due to asymmetric position of the star image within the slit opening.

If, as in this case, the investigation is limited to early-type spectra, where the lines are single, loss of purity will have very little effect and case (*a*) may be omitted from consideration. Even in spectra of the solar type where ordinarily high purity is desirable, it seems

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[1] *Astrophysical Journal*, 27, 139, 1908.

likely that, if measured on the spectrocomparator, the loss of accuracy will be due mainly to increase in the accidental errors of setting.

Limiting ourselves therefore to the two sources (*b*) and (*c*) of error, it is evident that they are in a sense entirely independent of each other. The former may be evaluated without considering the latter by treating the residuals from the measures of the star lines on a sufficient number of plates, the residuals for the lines on each plate being obtained from the mean velocity for that plate. The effect of the latter can be obtained only from such a number of complete velocity determinations, that the systematic displacements due to source (*c*) may be considered accidental. Even then the effect will be masked by the accidental errors of measurement due to cause (*b*) and possibly by systematic displacements due to other causes. Again, in source (*b*) it is evident that the width and diffuseness of the lines depend upon the relative lengths of camera and collimator, equal focal lengths evidently giving more diffuse lines than in the case where the collimator is longer than the camera. This and other considerations led to the test being made with three dispersions of the spectrograph. The collimator focus was 525 mm in each case.

I. One-prism spectrograph, Brashear Single Material camera objective of 525 mm focus; linear dispersion 30.1 tenth-meters per millimeter at $H\gamma$.

II. Three-prism spectrograph, Zeiss "Chromat" camera objective of 525 mm focus; linear dispersion 10.2 tenth-meters per millimeter at $H\gamma$.

III. Three-prism spectrograph, Ross "Homocentric" camera objective of 275 mm focus; linear dispersion 18.2 tenth-meters per millimeter at $H\gamma$.

In the last dispersion, the Ross camera lens was not free from aberration and curvature of field; moreover, owing to a temporary mounting no temperature control could be applied. Results in this case were consequently considered less worthy of confidence, and only three slit-widths, 0.025, 0.051, and 0.076 mm, were tested as compared with four, 0.025, 0.038, 0.051, and 0.076 mm, in dispersions I and II.

The star chosen for the experiments was β *Orionis*, which contains several lines of only moderate sharpness, thus making the test as general as possible, obtaining, so far as may be from one star, the effect of increasing the slit-width upon the accuracy of measurement of both sharp and diffuse lines. Its brightness is such as to render only short exposures necessary, although, as will be seen later, this may not be an advantage so far as systematic displacements due to cause (*c*) are concerned.

It may be of interest to give the average exposures required for the different slit-widths in the three dispersions, as indicating the time saved by the use of the wider slits.

DISPERSION	EXPOSURE TIME FOR SLIT-WIDTHS			
	0.025	0.038	0.051	0.076
I...........	2.5 min.	1.5 min.	1 min.	0.75 min.
II...........	14	10	8	5
III...........	5		3	2

Although it was recognized that more trustworthy results would have been obtained by double the number, the spectra made at each slit-width, owing to the labor involved in the measurement, were limited to six. Of the 66 plates, 18 were measured by Mr. Harper, the balance by myself. About 15 lines, star and comparison, were measured on each plate which, with eight settings to the line, makes nearly 8000 settings of the micrometer screw.

The same lines, both star and comparison, were measured on all plates of the same dispersion, but these lines changed as the dispersion changed, owing to the longer range in the single-prism instrument and to differences in the best lines available in the other two cases. The lines *Mg* 4481.400, *He* 4471.676, and $H\gamma$ were measured in all the spectra. There were measured, in addition, in the single-prism plates $H\delta$, *He* 4026.352, and K; in the three-prism plates with the short-focus camera *Si* 4131.047, *Si* 4128.211, and $H\delta$, and in the three-prism plates with the long-focus camera *He* 4388.100. In some of the latter the lines 4131, 4128, and $H\delta$ were also measured.

All measures were reduced to velocities by a modification of Hartmann's method.[1] Each line was weighted during the measurement and the velocity of the plate obtained from the weighted mean. As

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[1] *Astronomische Nachrichten*, **155**, 110, 1901.

stated before, the residuals for each line in the plate were obtained from the weighted mean of that plate, and the residuals of all the lines in the six plates of a series were treated to obtain the relative accuracy of that series. It is evident that the probable error of a line of unit weight will not necessarily give the relative accuracy of the series, as the weights given to the lines in different series may not be consistent. Hence it has seemed preferable to obtain the probable error of a line of average weight as a measure of the relative accuracy of a series, so far as it depends upon accidental errors of measurement.

For systematic errors due to asymmetric position of the star image with respect to the slit-jaws, the best that can be done is to obtain the probable error of a plate from the six plates of a series. Although the number of measures is too small, and the plates are affected with accidental errors as well as possible systematic displacements due to other causes, nevertheless the relative values for different slit-widths will indicate whether systematic displacement is liable to occur when the slit is widened.

These probable errors are obtained from two or three groupings of the lines in each dispersion. The three lines 4481, 4472, and 4341 formed one group in all the plates. In addition in the single-prism plates a group of all the seven lines was formed; in the three-prism long focus, of the four lines 4481, 4472, 4388, and 4341; and in the three-prism short focus two additional groups (*a*) of the lines 4481, 4472, 4341, 4131, and 4128, (*b*) of all the seven lines measured. These different groupings entailed little additional labor and served to give some idea of the relative values of the lines.

The three lines 4481, 4472, 4341 are of by far the best quality for measurement in all the plates, and besides are near the position of minimum deviation, λ 4415, the axis of the camera lens and the point of minimum focus or turning-point of the color-curve of objective and corrector. As will be seen, the probable errors are considerably smaller when these three lines only are used than when they are combined with others of poorer quality.

It has not seemed necessary in this case to tabulate the separate measures, but only to give the probable errors in kilometers per second of the different series for the different groupings of lines.

ERRORS

Dispersion	Slit-Width	Probable Error Line of Average Weight			Probable Error Single Plate		
		3 Lines		7 Lines	3 Lines		7 Lines
	mm						
One Prism	0.025	4.6		5.3	1.7		1.3
Camera of 525 mm focus	.038	2.5		4.8	2.7		2.5
	.051	2.4		5.2	3.0		1.5
	.076	4.4		7.5	7.7		5.2
		3 Lines	4 Lines		3 Lines	4 Lines	
Three Prisms	.025	2.3	2.3		1.5	1.7	
Camera of 525 mm focus	.038	2.1	2.8		1.3	1.2	
	.051	2.5	3.0		0.7	0.8	
	.076	2.1	3.1		0.9	1.4	
		3 Lines	5 Lines	7 Lines	3 Lines	5 Lines	7 Lines
Three Prisms	.025	2.9	2.8	5.6	2.1	3.2	2.4
Camera of 275 mm focus	.051	2.9	3.2	4.8	3.0	3.8	4.2
	.076	3.8	4.0	6.4	2.9	3.8	5.0

The above summary of probable errors shows some curious and unexpected results.

With the single-prism spectrograph, the accidental error of setting as measured by the probable error of a line of average weight shows no increase for increase of slit-width from 0.025 to 0.051 mm, but a further widening to 0.076 mm causes an increase of about 50 per cent. in the accidental errors. The error due to non-central position of the star image within the slit-jaws, as measured by the probable error of a plate, shows an even more marked increase of about 200 per cent. with a slit 0.076 mm wide. As the exposures for this width were only about 45 seconds each, it is probable that, during an exposure, the star image was not on the whole centrally situated, causing systematic displacements of the star lines, variations in the velocities of the plates, and consequent increase of probable error. A position 0.004 mm to one side of the center would cause an error of about 10 km. If the exposure had been longer, the vagaries of seeing and guiding would probably insure a mean position nearly central and consequent freedom from systematic error. This is well shown in the higher dispersions, where the exposure times were 6 and 2.5 minutes and where, in the former, the systematic error for slit-width 0.076 mm is less than for slits 0.025 and 0.038 mm. It may be of interest to mention in this connection an apparent systematic difference between the velocities obtained with wide and narrow slits. They show on the whole a smaller positive value of about 2 km for the wider slit-widths. This may be due to a personal error in guiding or to some peculiarity in the optical path from the slit to the eye which systematically causes the image to be held to one side of the center of the opening.

With the three-prism spectrograph and the 525 mm camera neither accidental nor systematic errors show any increase with increase of slit-width, and so far as stars of this type are concerned apparently as accurate measures and as reliable results can be obtained with a slit 0.076 mm wide as with 0.025 mm. The exposure time in the former case is only about one-third that of the latter thus allowing a considerable increase of output.

With three prisms and 275 mm camera there is a slight increase in the errors with increase of slit-width but this is not marked and may be partly accounted for by the aberration of the lens and the lack of temperature control.

Summarizing the whole question we may conclude that, in early-type stars, a slit at least 0.051 mm wide may be used without appreciably increasing the errors of setting on the lines or introducing any systematic displacement. In the case of the higher dispersions the slit may be widened to 0.076 mm without diminishing the accuracy of velocity determinations. The same thing may also be true in single-prism work with fainter stars where the exposure will be longer than a few minutes. It must not, however, be forgotten if the spectrum has faint metallic lines as in *Sirius* or *Vega*, that an increase in slit-width will diminish the contrast, and, with a slit as wide as 0.076 mm, will cause the fainter lines to disappear.

A study of the residuals leads to some other interesting points to which, although foreign to the subject of this paper, I may just briefly refer.

The residuals of $H\delta$ from 18 plates with the single-prism and 12 plates with the three-prism spectrograph give a mean correction to wave-length 4102.000 of -0.152 tenth-meters, showing a change in the same direction although of slightly greater magnitude than that adopted by Campbell and Wright.[1] However, owing to the character

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[1] *Astrophysical Journal*, 9, 50, 1899.

of the spectrum, considerably greater weight should be attached to their values.

The residuals from $H\beta$ are so high and so irregular, being sometimes positive and sometimes negative with all three dispersions and all slit-widths, that no confidence can be placed in the measurement of this line and it would be preferable to omit it. This may be, in part, due to the character of the line itself, and in part, to the fact that the star image is considerably out of focus at $H\beta$, resulting in an enlarged disk and consequent non-uniform illumination of the collimator and camera lenses. There is also at this part of the field considerable vignetting of the pencil, which will not help matters.

In the case of lines to the violet end, however, the residuals do not indicate any systematic difference nor are they of greater magnitude than is to be expected from their character. The star focus in this case is not so far beyond the slit, and besides the vignetting does not affect them to so great an extent.

In conclusion, it gives me pleasure to acknowledge the interest shown and encouragement given in this work by the director, Dr. W. F. King.

Dominion Observatory, Ottawa
August 1908

THE SPECTROSCOPIC BINARY ψ *ORIONIS*

BY J. S. PLASKETT

The star ψ *Orionis* ($\alpha = 5^h\ 21^m.6$; $\delta = +3^\circ\ 1'$; Phot. Mag. 4.5) was announced as a spectroscopic binary by Frost and Adams[1] in 1903. Upon learning from Mr. Frost that its orbit was not under investigation at the Yerkes Observatory, it was placed under observation here on November 11, 1907. The last of the 40 plates secured was made on March 16, 1908, and all of these except three, which were too weak for measurement, have been used in the determination of the orbit. The instrument used was the single-prism spectrograph of the Dominion Observatory which has a linear dispersion of 30.2 tenth-meters per millimeter at $H\gamma$ and gives the whole visible spectrum in sharp focus. A visual objective and correcting lens, however, limits the usable region to that between and including $H\beta$ and K.

The spectrum of ψ *Orionis* is of the helium type with very broad and diffuse lines of helium and hydrogen. Their measurement is difficult and the resultant velocities subject to considerable uncertainty, a measure of this being given by the probable error, ± 6.8 km, of an observation of unit weight. The lines, although diffuse, are in general fairly symmetrical and in consequence more easily measured than in the case of ι *Orionis* recently discussed.[2] Furthermore, owing to the extremely high range in the velocity, about 288 km, and to the low eccentricity, the elements of the orbit can be satisfactorily determined notwithstanding the high probable error of a plate.

The lines measured in the spectrum of ψ *Orionis*, with the velocities corresponding to one revolution of the micrometer screw (0.5 mm pitch) are given in the accompanying table.

The lines λ 4713 and λ 3970 were not often measurable and have been used only a few times. The number of lines measured varied from 4 to 9, except that in one plate only 3 were used. Most of the

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[1] *Astrophysical Journal*, **17**, 246, 1903.

[2] *Ibid.*, **27**, 272, 1908.

TABLE I

LINES IN ψ *Orionis*

Element	Wave-Length	Velocity per Revolution
$H\beta$	4861.527	1451.
He	4713.308	1332.
He	4471.676	1143.
He	4388.100	1080.
$H\gamma$	4340.634	1044.
He	4143.928	898.
He	4120.973	881.
$H\delta$	4102.000	868.
He	4026.352	814.
$H\epsilon$	3970.177	774.

measures have been made by myself, although I am indebted to Mr. Harper and Mr. Westland for the measures of several and for the remeasurement of some giving larger than normal residuals. The velocities were generally only slightly changed by the second measurement.

The data of the 37 plates are given in Table II, the phase being obtained from the period finally determined, 2.52588 days, using for initial epoch Julian day 2,417,914.0.

The determination of the period entailed some difficulty and it was not until about 25 plates had been measured that an approximate value was obtained. High positive and negative velocities repeated themselves every 5 days, but this period would not suit intermediate values. A trial of 2.5 days showed traces of periodicity which was enhanced by slightly lengthening. Finally, the Ottawa observations, extending over 50 periods, grouped themselves most favorably under a value of 2.526 days which agreed well with the three 1903 observations of Frost and Adams, the effect of introducing the latter being to slightly diminish the value. For a preliminary value 2.526 days was chosen.

Following the practice here and elsewhere for stars of this type, in which accurate velocities are unobtainable, the elements of the orbit were first determined by graphical methods, different values being rapidly tested by the method of Dr. W. F. King.[1] After considerable adjustment, satisfactory elements, which agreed well with

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[1] *Astrophysical Journal*, 27, 125, 1908.

TABLE II

MEASURES OF ψ *Orionis*

Plate No.	Julian Date	Phase	Velocity	No. of Lines
1138.........	2,417,891.836	.569	+ 41.7	8
1158.........	903.717	2.347	−145.5	4
1182.........	914.830	.830	+135.8	9
1183.........	914.857	.857	+139.1	8
1195.........	938.667	1.934	− 45.5	8
1196.........	938.698	1.965	− 70.2	8
1208.........	942.764	.979	+145.9	8
1209.........	942.792	1.007	+148.0	8
1214.........	944.639	.328	− 7.0	8
1215.........	944.667	.356	− 5.0	9
1220.........	954.726	.312	− 5.5	7
1221.........	954.750	.336	− 11.6	6
1227.........	955.556	1.142	+143.0	8
1233.........	957.496	.556	+ 51.0	7
1238.........	961.539	2.073	−114.5	7
1239.........	961.578	2.112	−117.2	7
1257.........	963.645	1.653	+ 16.5	6
1264.........	964.585	.067	−101.2	6
1271.........	965.534	1.016	+139.9	7
1279.........	968.487	1.444	+116.2	5
1283.........	968.598	1.555	+ 56.6	5
1296.........	970.459	.890	+144.5	6
1301.........	970.626	1.057	+153.8	4
1304.........	970.710	1.141	+151.6	5
1312.........	975.556	.935	+145.3	7
1317.........	980.542	.869	+126.0	8
1319.........	980.677	1.004	+140.5	6
1321.........	989.534	2.283	−140.4	8
1333.........	990.510	.734	+103.9	6
1334.........	992.547	.245	− 49.0	6
1336.........	993.667	1.365	+103.3	5
1344.........	994.499	2.197	−136.7	6
1347.........	994.685	2.383	−135.1	6
1349.........	996.531	1.703	+ 34.3	7
1376.........	8,005.643	.711	+110.2	3
1384.........	010.642	.659	+ 95.6	5
1395.........	017.510	2.475	−135.0	7

the observations, were obtained. A diagram of the corresponding velocity-curve with the observations shown as circles appears in Fig. 1.

The elements of the orbit are:

Period = 2.526 days
$e = 0.063$
$\omega = 186°$
$K = 147.2$ km
$\gamma = +12.42$ km
$a \sin i = 5,103,000$ km
$T = 2.36$ days = Julian Day 2,417,916.36

This solution had been completed and was considered final when Dr. Schlesinger, to whom I am much indebted for this and other valuable suggestions, advised the application of a least-squares correction to the orbit of *ι Orionis.* Without having given much consideration to the matter, and influenced probably by the practice of other observers in stars of similar type, it had always appeared to me that in observations with high residuals not much would be gained. However, such a correction applied to *ι Orionis* (see p. 274) showed a large reduction of Σpvv and it was thought desirable to make a similar solution for *ψ Orionis.*

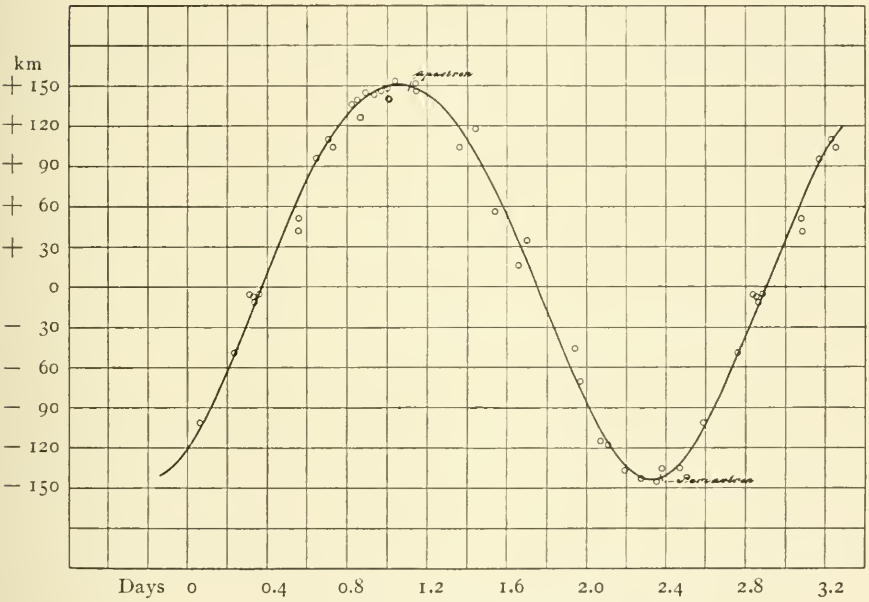

FIG. 1.—Preliminary Velocity-Curve of *ψ Orionis.*

It will be noticed that by far the highest residuals occur in the ascending and descending branches of the curve. This may be due to an error in the period or to the fact that, owing to changes in the seeing or to clouds during part of the exposure, the effective mean date of these exposures is not the same as the actual mean time entered. This latter cause might have considerable effect in a star of short period. Taking cognizance of the former cause, it was deemed advisable to consider at first the Ottawa observations only and to obtain from them, if possible, a correction to the period.

Reducing the 37 observations to 29 places by combining plates taken successively on the same nights, weighting them accordingly, and computing from each, by the elements obtained above, the coefficients for the five unknowns (method of Lehmann-Filhés[1]) with the addition of an unknown, of coefficient unity, for the velocity of the system, we obtain 29 observation equations connecting these six unknowns with the residuals between the observed and computed values of the velocity. To make the observation equations homogeneous the following substitutions were made:

$$x=\delta K \qquad u=\frac{100K}{(1-e^2)^{\frac{3}{2}}}\delta\mu=14801.7\delta\mu$$

$$y=K\delta e=147.2\delta e \qquad v=\frac{K\mu}{(1-e^2)^{\frac{3}{2}}}\delta T=368.18\delta T$$

$$z=K\delta\omega=147.2\delta\omega \qquad w=\delta\gamma$$

There result the following normal equations:

$$\begin{array}{rrrrrrr}
20.398x- & 5.255y+ & 2.618z+ & .471u- & 2.431v & +\ 5.297w+85.859=0 \\
 & +20.726y+ & 1.446z+ & .288u- & 1.687v & -\ 5.132w-31.490=0 \\
 & & +15.514z+ & 7.241u- & 15.392v & +\ 4.702w+55.912=0 \\
 & & & +5.291u- & 7.169v & +\ 1.401w+13.180=0 \\
 & & & & +15.337v & -\ 4.291w-54.156=0 \\
 & & & & & +37.000w+38.800=0
\end{array}$$

It will be noticed that the normals in z and v ($\delta\omega$ and δT) are practically identical and it will be impossible accurately to determine their values separately owing to the smallness of the coefficients in the elimination. Consequently $\delta\omega$ and δT were successively assumed to be zero, and we obtain the following corrected elements from the two solutions.

	Preliminary	For $\delta T=0$	For $\delta\omega=0$
K	147.2	143.843	143.799
e	0.063	0.06992	0.07012
ω	186°	183°.736	186°
Period U	2.526 days	2.52561	2.52563
T	2.36 days	2.36	2.3753
γ	+12.42	+12.517	+12.453

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[1] *Astronomische Nachrichten*, 136, 17, 1894.

As there is relatively less change in T than in ω in the two cases, the first set only will be considered.

The change in the period is small, showing that no improvement can be effected in the Ottawa observations by any marked change in this variable and it can now be finally determined by means of the three early observations of Frost and Adams with the aid of three additional plates kindly sent me by Mr. Frost. Two of the latter, the third being unsuitable, were carefully measured by Mr. Harper and the use of the five measures, three of 1903, one each of 1904 and 1905, gave as the only permissible period 2.52588 days, which cannot be in error more than one unit in the last place. The positions of these observations on the curve are shown by the crosses in Fig. 2. The residuals are no larger than is to be expected from spectra so uncertain and difficult of measurement as these.

In the final solution, then, a correction for the period was omitted. As provisional elements (in round numbers) those obtained by the first solution were taken.

$$\begin{array}{ll}
\text{Period}=2.52588\text{ days} & \omega=185^\circ \\
K=144.0 & T=2.36\text{ days} \\
e=0.07 & \gamma=+12.5\text{ km.}
\end{array}$$

The observations with their corrected phases, given in Table II, were grouped into 19 normal places (Table III), from which were obtained 19 observation equations. Using the same substitutions for homogeneity as before there result the normal equations

$$\begin{array}{rrrrrr}
20.556x & -5.145y & +2.629z & -2.397v & +5.351w & -1.617=0 \\
 & +20.106y & +1.334z & -1.600v & -5.639w & +13.118=0 \\
 & & +15.614z & -15.465v & +4.656w & +14.165=0 \\
 & & & +15.398v & -4.282w & -13.127=0 \\
 & & & & +37.000w & +16.670=0
\end{array}$$

Again the normals in z and v are nearly identical. Assuming V or $\delta T=0$ the solution gives

$$\begin{array}{rl}
x=+0.1198 & \delta K=+0.1198\pm 1.582\text{ km} \\
y=-.7099 & \delta e=-.00493\pm .01116 \\
z=-.7225 & \delta\omega=-.005015=-.286^\circ\pm .710^\circ \\
w=-.4851 & \delta\gamma=-.4851\pm 1.177\text{ km}
\end{array}$$

giving for the final elements:

$$K=144.12\pm 1.58\text{ km}$$
$$e=0.0651\pm .0112$$
$$\omega=184\overset{\circ}{.}71\pm .71^\circ$$
$$U=2.52588\text{ days}$$
$$T=2{,}417{,}916.36\text{ Julian date}$$
$$\gamma=+12.015\text{ km}\pm 1.177\text{ km}$$
$$a\sin i=4{,}995{,}100\text{ km.}$$

TABLE III

NORMAL PLACES

No. of Plates	Total diff. of phase	Mean phase from T	Mean Velocity	Wt.	C.—O. Preliminary	C.—O. Final	Eph.—Equation
2........	.036	.005	−140.3	2	− 2.7	− .5	.00
1........		.115	−135.0	1	+ 6.6	+ 5.4	+.18
1........		.233	−101.2	1	− 2.5	− 2.7	+.02
1........		.411	− 49.0	1	+ 4.1	+ 2.0	−.17
4........	.044	.499	− 7.3	4	− 4.6	− 7.5	−.02
2........	.013	.7285	+ 46.4	2	+22.9	+18.6	−.05
1........		.825	+ 95.6	1	+ 1.5	− 2.9	−.08
2........	.023	.8885	+107.0	2	+ 5.9	+ 1.1	−.03
3........	.039	1.018	+133.6	3	− .1	− 1.6	−.02
3........	.089	1.101	+144.7	3	+ 1.0	− 3.3	−.01
4........	.053	1.187	+145.6	4	+ 4.5	+ .7	−.01
2........	.001	1.3075	+147.3	2	+ .1	− 2.8	.00
2........	.079	1.5705	+109.7	2	− 2.6	− 2.7	+.05
1........		1.711	+ 56.6	1	+12.0	+13.4	−.04
2........	.050	1.844	+ 25.4	2	− 1.1	+ 1.7	+.01
2........	.031	2.1155	− 58.2	2	−14.6	−10.3	−.02
2........	.039	2.2585	−115.8	2	+ 1.2	+ 5.4	−.01
1........		2.363	−136.7	1	+ 1.8	+ 5.2	+.25
1........		2.449	−140.4	1	− 2.7	+ .3	−.08

A comparison (Table III) of the residuals obtained on the one hand by computing an ephemeris from these elements and on the other by substituting the values of the unknowns in the observation equations shows that the solution is satisfactory. The resulting velocity-curve with the normal places plotted as circles is given in Fig. 2. Σpvv is reduced from 1970.3 to 1522.5, the probable error of an observation of weight unity from ±7.7 km to ±6.8 km. The only change from the original elements of appreciable magnitude is in K which is reduced by about 3 km. Three rather high residuals, all occurring on the inclined parts of the curve, may account for part of this change. As previously mentioned, part of the discrepancy in these three places, beyond that due to the character of the spectrum, may be explained, in a very short period binary, by inaccuracy in phase determination due to unsymmetrical exposure. The very large range of velocity, 288 km, the highest in this type of binary known to the writer, is undoubtedly a considerable factor in obtaining satisfactory elements which in this case may be considered as fairly closely determined. Apparently, as in ι *Orionis*, the least-squares solution has improved the geometrically determined elements.

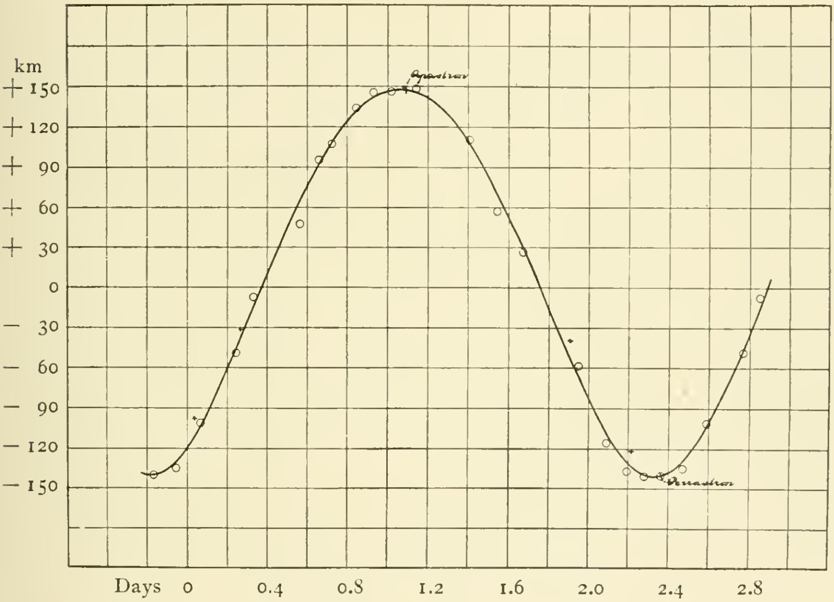

FIG. 2.—Final Velocity-Curve of ψ *Orionis*

In conclusion I wish to express my obligations to the director, Dr. W. F. King, for the advice he has given and the interest he has shown in this work.

DOMINION OBSERVATORY, OTTAWA
July 1908

THE ORBIT OF *ι ORIONIS*

BY J. S. PLASKETT

Acting on a suggestion kindly made to me by Dr. Schlesinger, a least-squares solution has been applied to the elements of the orbit of *ι Orionis* recently published in this *Journal.*[1] As preliminary elements those determined in the above paper were taken, and the 113 plates were grouped into 26 normal places, the same as before except for some minor changes introduced by a consistent system of weighting. An ephemeris having been computed from these elements, the coefficients of the unknowns in the observation equations were calculated from the formulae of Lehmann-Filhés[2] for each of these places. The period was considered as very closely determined by the method previously used and a correction considered unnecessary.

From the observation equations were formed the normal equations below, the following factors being introduced for homogeneity:

$$x = \delta K$$
$$y = K\delta e = 112\delta e$$
$$z = K\delta\omega = 112\delta\omega$$
$$u = \frac{K\mu}{(1-e^2)^{\frac{3}{2}}}\delta T = 83.46\delta T$$
$$v = \delta\gamma$$

NORMAL EQUATIONS

$$\begin{array}{rrrrrr}
+44.968x & -\ 29.522y & +\ 3.322z & +\ 0.327u & -14.291v & +\ 98.606=0\\
 & +228.507y & -41.899z & +65.630u & +39.089v & -244.074=0\\
 & & +51.724z & -53.431u & -33.929v & -\ 33.442=0\\
 & & & +76.940u & +25.424v & -\ 56.373=0\\
 & & & & +95.000v & -\ 15.800=0
\end{array}$$

The solution of these equations gave the following corrected elements:

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[1] *Astrophysical Journal*, **27**, 272, 1908.

[2] *Astronomische Nachrichten*, **136**, 17, 1894.

	Preliminary	Corrected
K	112.0	109.92
e	0.75	0.7552
ω	110°	113°.31
T	1.94 days	1.991 days
γ	+20.7 km	+21.34 km
Period	29.136 days	29.136 days
$a \sin i$	29,680,000 km	28,867,000 km

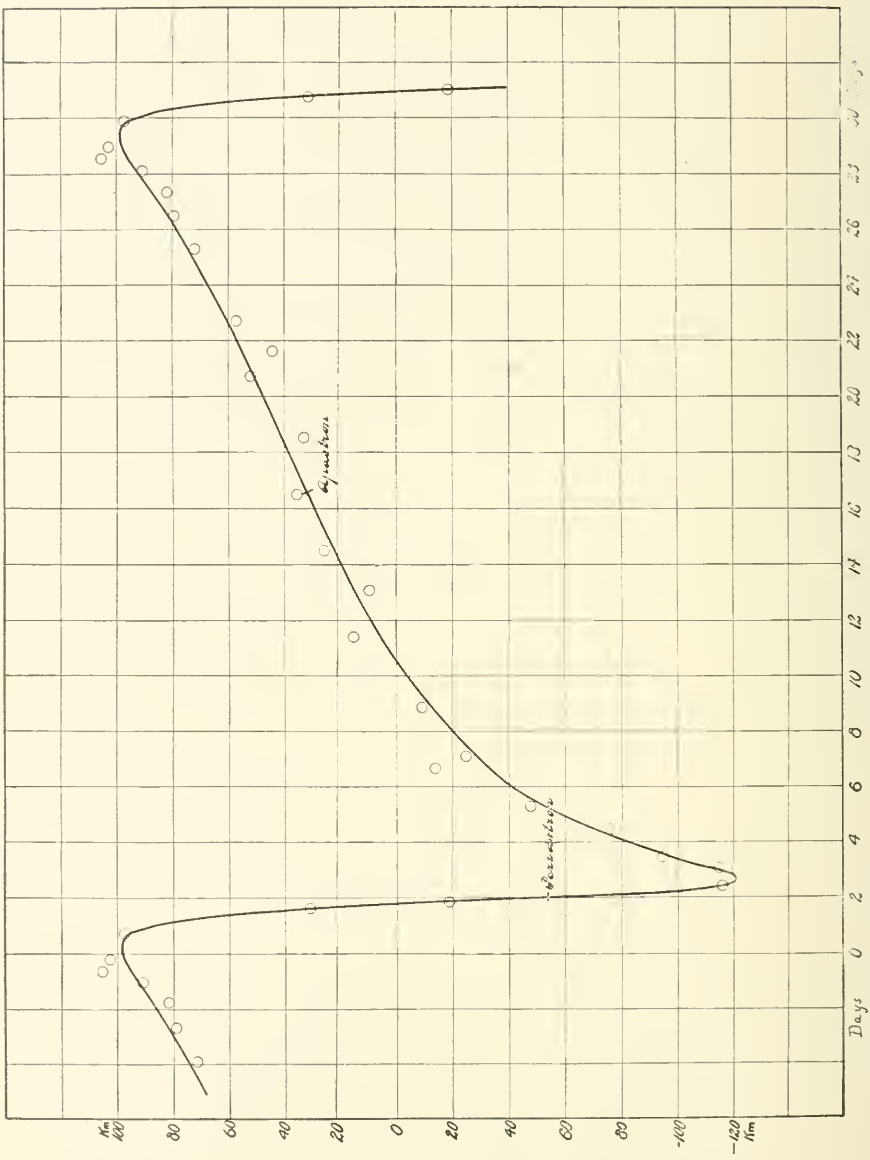
A comparison of the residuals obtained from an ephemeris and from substitution in the observation equations showed some differences of over a kilometer and a second solution was necessary. For preliminary elements those obtained in the first solution, except T, which was increased to 2.01 days, were used. The change in T was due to a better agreement thereby produced in the residuals. Using the same substitutions for homogeneity there result the normal equations

$$\begin{array}{rrrrrr}
+45.058x & -\ 28.047y & +\ 2.576z & +\ 0.726u & -14.660v & -\ \ 0.731=0 \\
 & +266.994y & -45.686z & +65.208u & +43.697v & +117.502=0 \\
 & & +50.372z & -48.247u & -33.053v & -\ 70.762=0 \\
 & & & +64.085u & +22.897v & +\ 95.820=0 \\
 & & & & +95.000v & +\ 34.800=0
\end{array}$$

Their solution gives for final elements the following:

K	109.90	±1.100 km
e	0.7543	± .0046
ω	113°.28	±1°.083
T	1.993	± .022 days = Julian Day 2,417,587.993
γ	+21.34	±0.856 km
Period	29.136 days	
$a \sin i$	28,907,000 km	

An ephemeris computed from these elements shows that Σpvv has been reduced from 2994 to 2181, the probable error of an observation of unit weight becoming ±6.88 km, while the probable errors of the elements become those given above. The changes from the first solution are very small but the agreement between the residuals is now satisfactory. The velocity-curve corresponding to the final elements is given in the accompanying figure, with the positions of the normal places as small circles. A comparison of



Velocity-Curve of *ι Orionis*

this with the previous figure shows that the general trend of the observations is more closely followed. The probability of a secondary disturbance seems somewhat less than with the original elements, and this is further lessened by a knowledge of the fact that the normal places with the highest residuals contain always one or more observations with the universal spectroscope where the temperature control was poor and the spectra contained only two measurable lines.

The result of this computation seems to justify Dr. Schlesinger's contention that, even in the case of spectra in which accurate measurement is impossible, the least-squares solution will give the best determination of the elements of a binary orbit.

Dominion Observatory, Ottawa
July 1908

PHOTOGRAPHIC LIGHT-CURVE OF THE VARIABLE STAR *SU CASSIOPEIAE*

By J. A. PARKHURST

The variation of this star (R. A. $2^{\mathrm{h}}\ 43^{\mathrm{m}}\ 2^{\mathrm{s}}9$; Dec. $+68° 28' 28''$ [1900]) was discovered by Müller and Kempf[1] from the discordance in their results obtained in 1903 and 1905 for the *Photometric Durchmusterung.* It received the provisional number 155.1906, and their measures (together with those by Graff) were published in December 1906.[2] Before this was received, a note by the writer, confirming the variation, was sent to the printer.[3] Lastly, von Zeipel[4] has published 23 measures with a Zöllner photometer made between February 16, 1907, and January 24, 1908.

As this star is within one degree of the *Algol*-type variable *RZ Cassiopeiae*, the plates taken for the latter by the extra-focal method and described in detail by Jordan and the writer[5] also serve to show the changes of *SU*.

The comparison stars used, as in the measures of *RZ*, were

B. D.	Potsdam Color Mag.	Adopted Spectrum Mag.
F +67° 224	GW 6.15	A 6.15
D +69° 171	.. ....	A 7.45

More plates were used than in the measures of *RZ* given in the article last quoted. A remeasurement of these plates, reduced with an improved absorption curve, gave by the method of the "absolute photographic scale" an interval of 1.30 magnitudes between the

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[1] *Potsdam Publications*, **16**, 254.

[2] *Astronomische Nachrichten*, **173**, 305, 1907.

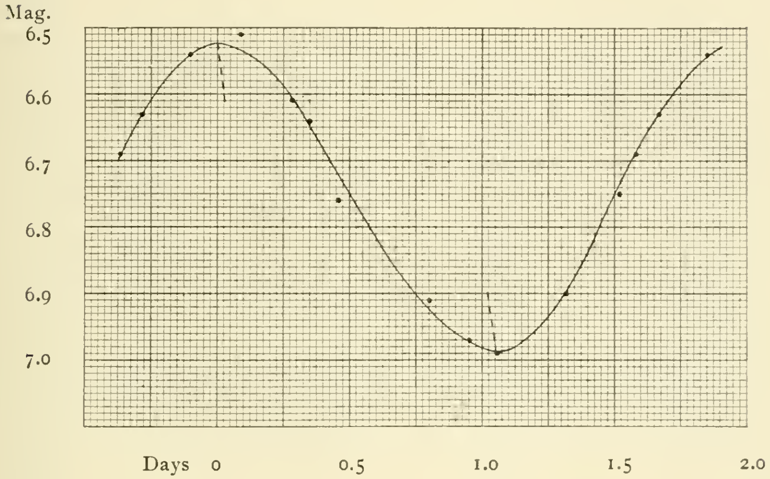
[3] *Astronomical Journal*, **25**, 136, 1907.

[4] *Astronomische Nachrichten*, **177**, 369, 1908.

[5] *Astrophysical Journal*, **26**, 244, 251, 1907.

stars *F* and *D*, making the adopted magnitude of *D* 7.45, which is 0.02 fainter than that adopted in the report on *RZ*.

The extra-focal images were measured with the Hartmann "mikrophotometer" and the magnitudes corrected for atmospheric absorption and for the position of the star on the plate. The period given in Müller and Kempf's elements of maximum



Photographic Light-Curve of *SU Cassiopeiae*

$$\text{J. D. } 7287.30+1^{\mathrm{d}}.9498 \text{ E}$$

was found to need a slight negative correction, the observations here given being satisfied by the elements

$$\text{J. D. } 7287.30+1^{\mathrm{d}}.9490 \text{ E.}$$

With these elements the 86 observations were grouped into 12 normal points given in Table II, from which the mean light-curve shown herewith was drawn. Table I gives in the several columns the current number, the plate number, the Julian day to hundredths in Greenwich mean time, the number of the epoch by the above elements, the phase from the preceding maximum in days, the magnitude, and the residual as found from the curve.

TABLE I

No.	Plate	Julian Day G. M. T.	E	Phase	Mag.	Residual
1	141	7503.56	110	1.87	6.49	−0.05
2		03.57		1.88	6.55	+0.01
3	199	7768.68	246	1.63	6.47	−0.06
4	200	68.82	247	0.12	6.44	−0.10
5		68.84		0.14	6.48	−0.06
6	203	72.65	249	0.05	6.48	−0.04
7		72.67		0.07	6.57	+0.05
8		72.68		0.08	6.56	+0.04
9	207	74.83	250	0.28	6.59	+0.03
10		74.85		0.30	6.57	−0.06
11		76.86	251	0.36	6.68	+0.01
12		90.61	258	0.47	6.75	+0.02
13	210	91.62		1.48	6.79	+0.02
14		91.64		1.50	6.76	0.00
15		91.65		1.51	6.69	−0.06
16		91.66		1.52	6.74	−0.01
17		91.68		1.54	6.67	−0.06
18		91.69		1.55	6.63	−0.09
19		91.70		1.56	6.78	+0.07
20		91.72		1.58	6.62	−0.08
21		91.73		1.59	6.61	+0.02
22		91.74		1.60	6.57	−0.11
23		91.75		1.61	6.59	−0.09
24	213	7821.60	274	0.27	6.66	+0.04
25		21.61		0.28	6.60	−0.02
26		21.62		0.29	6.59	−0.04
27		21.63		0.30	6.63	0.00
28		21.64		0.31	6.55	−0.09
29		21.65		0.32	6.62	−0.02
30		21.66		0.33	6.57	−0.08
31		21.67		0.34	6.59	−0.06
32	214	23.66	275	0.39	6.73	+0.03
33		23.67		0.40	6.73	+0.03
34		23.68		0.41	6.76	−0.06
35	222	30.58	278	1.46	6.75	−0.05
36	224	30.63	278	1.51	6.77	+0.02
37		30.66		1.54	6.81	+0.08
38		30.69		1.57	6.73	+0.03
39		30.72		1.60	6.69	+0.01
40	227	32.60	279	1.53	6.78	+0.04
41	231	32.66		1.59	6.73	+0.04
42		32.67		1.60	6.72	+0.04
43	232	33.70	280	0.68	6.76	−0.09
44		33.71		0.69	6.93	−0.07
45	233	34.73		1.71	6.63	+0.02
46		34.75		1.73	6.60	0.00
47	234	34.77		1.75	6.57	−0.02
48	251	44.57	285	1.81	6.55	−0.02
49		44.59		1.83	6.56	0.00
50	254	49.55	288	0.94	6.92	−0.05
51		49.57		0.96	6.91	−0.06
52	255	49.60		0.99	6.89	−0.09
53	256	51.54	289	0.98	7.05	+0.07
54		51.55		0.99	7.02	+0.04

TABLE I—*Continued*

No.	Plate	Julian Day G. M. T.	E	Phase	Mag.	Residual
55..........	258	7851.68		1.12	7.02	+0.04
56..........	262	53.56	290	1.05	7.01	+0.02
57..........		53.57		1.06	7.07	+0.08
58..........	265	54.57	291	0.11	6.47	−0.05
59..........		54.58		0.12	6.53	0.00
60..........	268	55.54		1.08	6.96	−0.03
61..........		55.56		1.10	6.99	+0.01
62..........		55.65		1.19	6.98	+0.02
63..........	272	56.89	292	0.48	6.75	0.00
64..........		56.90		0.49	6.81	+0.05
65..........	276	59.57	293	1.21	7.03	+0.08
66..........		59.62		1.26	6.98	+0.04
67..........	279	59.70		1.34	6.87	−0.02
68..........		59.76		1.40	6.93	+0.08
69..........	284	82.67	305	0.93	6.99	+0.03
70..........	286	83.55		1.81	6.55	−0.02
71..........		83.56		1.82	6.49	−0.07
73..........		83.57		1.83	6.62	+0.06
74..........	288	84.53	306	0.84	6.99	+0.07
75..........		84.54		0.85	6.90	−0.03
76..........	288	84.58	306	0.89	6.92	+0.03
77..........	291	86.51	307	0.87	6.97	+0.03
78..........		86.52		0.88	6.86	+0.07
79..........		86.56		0.92	6.92	−0.04
80..........		86.57		0.94	6.95	−0.02
81..........	293	86.60		0.96	7.06	+0.09
82..........	300	91.55	361	0.66	6.89	+0.04
83..........	302	91.61		0.72	6.85	−0.02
84..........	303	99.55	365	0.87	6.96	+0.01
85..........		7999.56		0.88	6.95	0.00
86..........	306	8037.59	384	1.87	6.56	+0.02

TABLE II

NORMAL POINTS FOR MEAN CURVE

Phase	Mag.	No.
d	M	
0.09	6.51	7
0.29	6.61	6
0.35	6.64	7
0.46	6.76	5
0.80	6.91	11
0.95	6.97	7
1.06	6.99	7
1.32	6.90	7
1.52	6.75	7
1.58	6.69	7
1.67	6.63	6
1.85	6.54	9

In the reductions, as explained in the article last cited, the mean of the photometer scale-readings for the stars *F* and *D* were taken as corresponding to the mean of the adopted magnitudes, 6.80, and the magnitudes of the standards and the variable stars were found by the use of the "absolute scale." If this scale had been corrected for each plate so as to make the interval between the standards 1.30 magnitudes in each case, the residuals given in the last column of Table I would be reduced to a slight extent; and such a procedure would be quite justified. But it was thought best in this case to use the uncorrected scale so as to show the capability of the "absolute scale" to represent magnitudes on a series of plates taken at different times and separately developed. The sources of error included in the residuals, in their estimated order of importance, are:

1. Local errors on the plate, due to lack of uniformity in the thickness of the sensitive film. In exceptional cases these might be as large as a quarter of a magnitude, but on these plates (24 on commercial, 12 on plate glass) they do not seem to have exceeded one- or two-tenths of a magnitude.

2. Differences in the gradation of the plate due to some peculiarity in the manufacture or development. The latter was kept as uniform as possible in agent, time, and temperature.

3. Errors in measurement of the plates. Judging by the mutual agreement of the photometer settings these were quite small. Three settings were made on each star-disc and if the range exceeded 0.02 magnitude, additional settings were made.

4. Errors in the adopted absorption curve of the photometer wedge. As this curve depends on several thousand settings on a large number of sensitometer plates, the errors are supposed to be small.

The combined effect of these causes is such as to make the calculated probable error of a single observed magnitude ±0.033.

The resulting mean light-curve shows a continuous variation with range of 0.47 from 6.52 to 6.99 magnitudes. The time from minimum to maximum is 0.90 day, or 46 per cent. of the period; therefore the rise is slightly faster than the decline.

As the visual magnitudes cited at the beginning of this paper are all based on 6.15 for the star *F*, the differences between visual and photographic magnitudes give directly the color-intensity. The respective ranges are:

	Maximum	Minimum
Müller and Kempf..........	5.93	6.26
Von Zeipel.................	5.92	6.32
Photographic...............	6.52	6.99

The color-intensities are therefore 0.59 or 0.60 at maximum and 0.73 or 0.67 at minimum, from Müller and Kempf and von Zeipel respectively. The best objective-prism plates show the spectrum of *SU* to be F 3 G in the system described by Jordan and the writer,[1] calling for a color-intensity of 0.62 at phase $1^{\mathrm{d}}28$. This agreement is very satisfactory.

The radial velocity of this star has been measured on nine plates taken with the Bruce spectrograph on the 40-inch refractor. On account of the faintness of the star only one prism could be used and four hours' exposure was required, so that no great accuracy could be expected in the results. The total range observed is from −1 to −16 km, but the data are insufficient to determine whether this range is real or whether it bears any relation to the cycle of light-change. More plates will be taken when the star comes again into position.

YERKES OBSERVATORY
May 1908

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[1] "The Photographic Determination of Star-Colors and Their Relation to Spectral Type," *Astrophysical Journal*, 27, 169, 1908.

THE REPRODUCTION OF PRISMATIC SPECTRUM PHOTOGRAPHS ON A UNIFORM SCALE OF WAVE-LENGTHS

By A. FOWLER and A. EAGLE

In the course of spectroscopic work it is sometimes useful to be able to make direct comparisons of photographs taken by the use of prisms with those obtained by means of gratings. For this purpose, owing to the varying dispersion of prisms, it is necessary to reproduce the prismatic spectrum on a uniform scale of wave-lengths corresponding to that of the grating photograph with which the comparison is desired.

The method of rectifying the prismatic spectrum which is here described was arrived at quite independently, but it has been found since that the same general procedure was suggested and applied by E. S. King in 1898.[1] In both cases the original negative is placed in front of the copying camera in an inclined position with the less refrangible end nearer the lens, and the plate or bromide paper on which the image is received is also inclined at an angle to suit the particular case.

Mr. King appears to have obtained his angles and distances by trial—by adjusting until three lines in the spectrum were on the desired normal scale. He did not so far as we know give general formulae which make the method readily applicable to particular cases, and it may be of interest to indicate how these are derived, especially as it can be shown that the method gives a more accurate normalization than might have been anticipated.

The adjustment by trial is moreover rather troublesome and unsatisfactory. Four things have to be varied, viz., two distances and two angles so as to satisfy three conditions simultaneously: (1) a normal spectrum, (2) the desired scale, and (3) good focus throughout.

The best approximation to the dispersion curve of a prismatic

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[1] Report of the Harvard Astrophysical Conference, *Science*, **8**, 454, 1898.

spectrum which has yet been found is that given by the well-known Cornu-Hartmann formula:

$$\lambda=\lambda_0+\frac{c}{s-s_0}.$$

where c, λ_0, and s_0 are constants, and λ is the wave-length corresponding to the scale-reading s. Practical experience has shown that this equation holds very closely over a long range of the spectrum, and the following analysis indicates that the accuracy with which a prismatic spectrum can be reduced to a normal one is equal to that with which it may be represented by the above equation.

Let L be a lens which will bring equidistant points lying on a plane AB perpendicular to the axis of the lens, into focus as a system of equidistant images on another plane CD.

Then we can show that points lying on an inclined plane PS will be brought into focus on another plane QT.

In the diagram let $EL=u$, $FL=v$, $PG=x$, $PH=y$, $QJ=X$, $QK=Y$, $\angle SEB=\phi$, and $\angle QFD=\psi$.

Treating the lens as a thin lens, we have $\frac{1}{v}+\frac{1}{u}=\frac{1}{f}$, where f is the focal length. Hence, Q being the image of P,

$$\frac{1}{PM}+\frac{1}{QN}=\frac{1}{f},$$

where M and N are the feet of the perpendiculars from P and Q to the plane containing the lens. Hence

$$\frac{1}{u-y}+\frac{1}{v+Y}=\frac{1}{f},$$

or

$$v+Y=\frac{f(u-y)}{u-y-f}; \tag{1}$$

subtracting $v=\frac{fu}{u-f}$ from each side we have

$$Y=\frac{yf^2}{(u-f)(u-f-y)}. \tag{2}$$

Also

$$\frac{X}{x}=\frac{LJ}{LG}=\frac{v+Y}{u-y}.$$

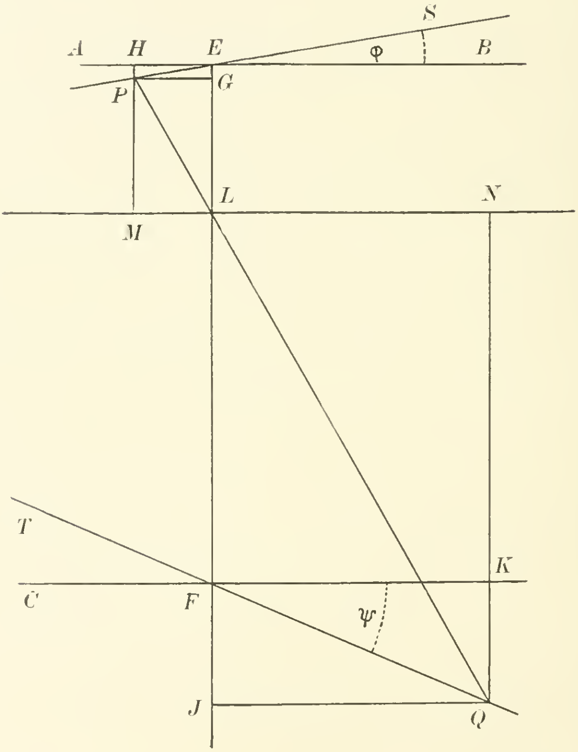
Using (1) we have

$$\frac{X}{x}=\frac{f}{u-f-y}; \tag{3}$$

combining (2) and (3) we obtain

$$\frac{Y}{X}=\frac{y}{x}\,\frac{f}{u-f}=\frac{y}{x}\,\frac{v}{u}, \qquad (4)$$

or, since $\frac{y}{x}$ is constant along PS we see that $\frac{Y}{X}$ will be constant. That is, all points lying on PS will be brought into focus on another straight line QT.



Equation (4) may be written

$$\tan\psi=\frac{v}{u}\tan\phi.$$

We require now to find how the dispersion varies along QT. Let $PE^2=s^2\equiv x^2+y^2$ and $QF^2=l^2\equiv X^2+Y^2$.

Then

$$l^2=\frac{f^2}{(u-f-y)^2}\left\{x^2+\frac{y^2f^2}{(u-f)^2}\right\}$$

from (2) and (3); or, putting $x=s\cos\phi$ and $y=s\sin\phi$

$$l=\frac{fs}{u-f-s\sin\phi}\sqrt{\cos^2\phi+\frac{v^2}{u^2}\sin^2\phi}\,.$$

For brevity write K^2 for the quantity under the radical sign, which is a constant with respect to s.

Then

$$l=\frac{fKs}{u-f-s\sin\phi}\,.$$

Hence

$$\frac{dl}{ds}=\frac{fK(u-f)}{(u-f-s\sin\phi)^2}\,.$$

Now if we have a prismatic spectrum on the plate PS for which the wave-length at the distance s from the center of the plate is given by

$$\lambda=\lambda_0+\frac{c}{s-s_0}\,,$$

we have

$$\frac{d\lambda}{ds}=\frac{-c}{(s-s_0)^2}\,.$$

Hence for the spectrum on QT we shall have

$$\frac{d\lambda}{dl}=\frac{d\lambda}{ds}\frac{ds}{dl}=\frac{c(u-f-s\sin\phi)^2}{fK(u-f)(s-s_0)^2}\,.$$

If now we can make $u-f-s\sin\phi$ always proportional to s_0-s, we see that $\frac{d\lambda}{dl}$ will be a constant independent of s; that is, the spectrum will be normal.

The condition for this to be so is evidently

$$u-f=s_0\sin\phi\,. \tag{5}$$

When this holds

$$\frac{d\lambda}{dl}=\frac{c\sin^2\phi}{Kf(u-f)}=\frac{c\sin\phi}{fKs_0}\,. \tag{6}$$

Now the value of $\frac{d\lambda}{dl}$ is known; it is the number of tenth-meters per centimeter we require in the normal spectrum. Let this be N.

Then from (6), on replacing K by its proper value—which may be written

$$\sqrt{\cos^2\phi+\frac{f^2\sin^2\phi}{(u-f)^2}} \text{ or } \sqrt{\cos^2\phi+\frac{f^2}{s_0^2}}$$

we have

$$N^2f^2(s_0^2\cos^2\phi+f^2)=c^2\sin^2\phi\,.$$

Hence

$$\sin\phi=\frac{Nf\sqrt{s_0^2+f^2}}{\sqrt{c^2+N^2f^2s_0^2}}\,. \tag{7}$$

Sin ϕ having been found from this equation the distance u is found from (5) and v is given by

$$v=\frac{fu}{f-u}=\frac{fu}{s_0\sin\phi}\,.$$

Lastly, the angle ψ is determined from the equation

$$\tan\psi=\frac{v}{u}\tan\phi=\frac{f}{s_0\sin\phi}\tan\phi=\frac{f}{s_0\cos\phi}\,. \tag{8}$$

From (5) and (8) we have

$$u+v=u+\frac{fu}{s_0\sin\phi}=\frac{(f+s_0\sin\phi)^2}{s_0\sin\phi}\,. \tag{9}$$

Equations (7), (8), and (9) give all the data required, viz., ϕ, ψ, and $u+v$.

We have found it convenient for the practical application of the process to replace the copying-board of the usual enlarging apparatus by one pivoted at the middle and provided at the back with a circular slot and clamp screw, a millimeter scale being let into the base so that its reading at once gives tan ψ. The swing-back of the camera which holds the negative readily permits adjustment of the angle ϕ. In practice the angles ϕ and ψ were set to their calculated values, as also was the total distance $u+v$ between the negative and the copying board. The focusing was done by moving the camera lens with the rack. When the enlargement is required to fit exactly some given scale or spectrum, the position of the lens is adjusted until this scale is exactly obtained in the image.

If the negative has been measured for the determination of wave-lengths, the constants of the Cornu-Hartmann formula will already have been obtained for it. It is necessary, however, to replace the constant s_0 obtained in the usual way by the value of $s-s_0$ for the center of the plate. This is of course the change introduced when s is measured from the center.

The following is an example showing the accuracy obtained. The equation of the prismatic spectrum obtained in the ordinary way—s being expressed in inches—is

$$\lambda=2566.60+\frac{50{,}951}{23.956-s}.$$

In this equation the scale reading of the line $\lambda=4859.93$ is 1.730. This line was 1.17 inches from the center of the plate so that the scale reading at the center was 2.90. Accordingly when s is measured from the center as origin, the equation becomes

$$\lambda=2566.6+\frac{50{,}951}{21.046-s'}.$$

On taking $N=30$ so as to obtain a normal spectrum on a scale of 30 tenth-meters to the inch, and taking the focal length of the lens as 5.93 inches, we find for this equation, by means of the previous formulae,

$$\tan\phi=0.076$$
$$\tan\psi=0.283$$
$$u+v=35.5 \text{ in.}$$

The negative was placed in the camera so that the center of the plate was on the axis of the lens. The enlargement was made on a plate which was measured afterward, and, a line near each end of the plate being taken as a standard, the wave-lengths of the intermediate lines were calculated by a linear interpolation formula. The figures indicate the results obtained for a portion of the iron arc.

λ observed	s (inches)	λ calculated	O.— C.
4823.697	.000	....	......
59.928	1.2095	.936	−.008
78.407	1.8248	.375	+.032
4903.502	2.6630	.490	+.012
24.956	3.3795	.960	−.004
34.245	3.6905	.279	−.034
46.568	4.1032	.642	−.074
66.270	4.7606	.343	−.073
94.316	5.6980	.431	−.115
5028.308	6.8315	.394	−.086
51.825	7.6153	.881	−.056
83.518	8.6728	.567	−.049
5110.574	9.5748	.593	−.019
27.533	10.1401	....	......

Thus, the greatest error in wave-length in a range of over 10 inches is about 0.1 tenth-meter. This corresponds to a displacement of a line of about $\frac{1}{300}$ of an inch. If half the range had been taken, the error would only have been one-quarter of this amount. Had our apparatus enabled us to set the angles more accurately, the errors could perhaps have been rendered still smaller than the above. The scale of the enlargement between the two extreme lines corresponds to 29.964 tenth-meters to the inch. The focusing was adjusted to give what appeared to be the best definition and not to give the exact scale, but the agreement is probably closer than could generally be expected. The same method has also been applied successfully to the production of normal frequency spectra.

If it be desired to compare two prismatic spectra which have different values of λ_0 they may both be reproduced as normal spectra on the same scale.

If the formulae be applied to normalize a prismatic spectrum which is on too small a scale, it will be found that the angles become too great to be practicable. This difficulty can, however, always be overcome by making intermediate ordinary enlargements in sections and then normalizing each section. It is not practicable to have $\tan\psi$ much greater than 0.5. This means that $s_0 \cos\phi > 2f$ by (8), or, since $\cos\phi$ is approximately unity, we have $s_0 > 2f$. This condition will at once enable us to see if the method is practicable in any given case.

When on the contrary the angles are small, simpler expressions may be found for them. In this case

$$\sin\phi = \frac{Nfs_0}{c},$$

and

$$\tan\psi = \frac{f}{s_0}.$$

The expression for $\sin\phi$ may be still further simplified. If λ_m is the wave-length at the center of the plate, i. e., corresponding to $s=0$, we have $(\lambda_m - \lambda_0)s_0 = c$. Hence

$$\sin\phi = \frac{Nf}{\lambda_m - \lambda_0}.$$

It will be seen that the angles are smaller, the smaller the focal length of the lens. We have found a lens of 6 in. focal length to work admirably in enlarging 3 or 4 in. of an original negative into a strip 15 in. long of a normal spectrum covering about 190 tenth-meters.

The focal length of the lens should be known fairly accurately, and a convenient way of finding it is to put a negative in the camera and focus it on the copying board in the usual manner. Then if d is the distance between two lines on the negative, d' the distance between their images, and l the distance from the negative to the copying board the focal length is given by

$$f = \frac{ldd'}{(d+d')^2}.$$

Imperial College of Science and Technology
London
July 1908

COMET *c* 1908 (MOREHOUSE)

BY E. E. BARNARD

Though comparatively faint and quiet in the visual telescope, this comet has shown extraordinary activity from a photographic standpoint. It is fair to say that no other comet has approached it in interest and importance since photography has been applied to these bodies. One remarkable advantage in its study has been the high northern declination of the comet, which for a time permitted exposures throughout the night. Advantage was taken of this fact to make series of photographs at intervals of one or two hours on several dates. By this means the complete history of some of the changes has been secured, so that it is possible to say just how this or that change took place. Some of the pictures show all these various stages of change.

The general tendency of the comet has been to produce a tail by a steady outflow of various streams of matter, but on several occasions great masses were thrown off which could be followed outward from the comet for several days before they finally dissipated into space. In some cases these masses were sufficiently dense to throw off streams or tails independently, in a similar manner to the parent comet. Very much material exists in these photographs for determining the motion of these masses, and when these are compared with photographs made elsewhere the entire motion of a mass from its original ejection until it melted away should be determinate.

The greatest changes in the comet, so far as covered by my photographs, occurred on September 30, October 1, and October 15. Those of September 30 and October 1 are the most interesting because of the beautiful and unique aspect of the comet during part of the time on September 30. The two plates (XXI and XXII) that accompany this paper give a good idea as to how the comet may utterly transform itself in a few hours.

The most remarkable transformation occurred on September 30 and October 1. It began between the 29th and 30th of September

PLATE XXI

South

COMET 1908 *c* (MOREHOUSE) ON SEPTEMBER 30, 1908, AT $14^h\ 22^m$ C. S. T. EXPOSURE $1^h\ 56^m$
10-Inch Lens of Bruce Telescope. Scale: 1 cm = 0°.36

PLATE XXII

South

Comet 1908 *c* (Morehouse) on October 1, 1908, at $13^h\ 43^m$ C. S. T. Exposure $2^h\ 0^m$
10-Inch Lens of Bruce Telescope. Scale: 1cm$=0^{\circ}.36$

and ended October 1. On September 30 a violent change was taking place throughout the night. Each exposure, separated by a couple of hours, showed a great variation in the comet. The last exposure on this date closed at $21^h\,20^m$ Greenwich M. T. The first exposure on October 1 began at $13^h\,9^m$. There is therefore an interval of about 16^h between these two pictures during which time the most remarkable part of the transformation must have taken place. If any photographs were made in England or on the continent during this time, they will be of the utmost importance in showing the process of the complete transformation of the comet on the dates specified. Any such photographs should be published—or at least their existence should be made known.

I have one photograph on September 29, $10^h\,45^m$, with an exposure of $2^h\,30^m$ through breaks in clouds. This shows a disturbed condition of the comet which possibly was the forerunner of the great change that followed in the next two days.

September 30. The first exposure was not especially remarkable. The head was rather small. From this a rather thick tail ran out in a straggling manner with a fainter sheeting of matter having a sharp edge on the south side. In the next picture the whole tail had moved out bodily and was connected with the head by a very narrow, tapering neck. The tail was wide and larger, widening out very greatly as it left the head. The northern part of the tail was the brightest and was greatly curved. Fluffy masses projected from the north side of this. In the third picture the comet had become a very remarkable and beautiful object, utterly different from the first picture. The tail had tapered down to a very narrow connection with the head which was very small and almost starlike. The fluffy masses had become a large projection from the north side of the tail. The appearance of the comet in this plate is unique and very beautiful. The tail appears cyclonic in form and structure. Doubtless an hour or so later the whole tail had become disconnected from the head, as the separation is essentially shown on the last plate. Such a complete separation of the tail from the head is actually shown in a photograph on September 20. It is really impossible properly to describe the remarkable transformation of the comet on this date. It is to be regretted that another picture was not made between the last one and daylight, but instead the time until 16½ hours was devoted to an exposure in another part of the sky.

The first of the pictures on October 1 showed, about 2° out from the comet, what was evidently the great mass of matter that formed the tail of September 30. The tail was almost 8° long. The outer 6° of this was made up of an irregular, long, straggling mass which had a tendency to spread northward. This great mass was apparently attached to the head of the comet by a slender thread, alongside of which to the south was another threadlike stream which, though connected with the mass, does not appear to quite reach the comet. There is a narrow, short ray from the head, at an angle of 45° with the tail on the south side.

In the second plate two rays connect with the great mass, one of which, after running parallel with the main one for a degree, bends in and joins it, making only one ray that reaches the head.

In the third plate there is a great change. A diffused ray has shot out from the head for a degree on the north side, while there are several streamers connecting the mass with the head. The fourth shows still greater changes. The new ray about a degree away merges into the straggling rays from the head to the mass. In the fifth, the new ray curves northward and then joins the system of rays from the head at a distance of 2°. In this plate the outward end of the ray system has become disconnected from the great mass, which has become square in form and more sharply defined at its end toward the head. In the sixth picture the separation is complete and the end of the great mass is more pointed.

On October 2 the comet had a changing system of broad curving streamers spreading out at wide angles. On October 3 the tail consisted of a widely diverging skeleton framework changing rather slowly and becoming rather complicated with new streams which in the last picture of that date were diffusing as if to join in making an ordinary tail, such as it had on the following night, October 4.

On October 15 another great disturbance occurred. The first photograph shows a straight narrow tail extending for half a degree with a short ray from each side of the head at angles of about 30° and 45°. At the end of the narrow tail ½° from the head begins a most extraordinary tail which is twisted and clouded at the beginning and which streams irregularly away, bending northward in irregular outline for 7° or 8° to the edge of the plate. In this first picture the straight tail joins the south portion of this twisted mass; and in the last picture of this date it makes a juncture farther north at about the middle of the mass which is ¼° broad where it begins. These masses are very dense and from the south part narrow streamers run out parallel with the short tail for about 2°. In the photographs of October 14 there were no indications of this disturbance. Remnants of these cloud masses, however, are shown much farther out in the photographs of October 16 and 17.

On October 15, after making the second exposure for that night, I developed my plates to see if the comet was in any way abnormal. As soon as I saw the remarkable appearance of the tail I at once began a new set of exposures and carried the comet as long as I could follow it in the haze and moonlight. There is therefore a good record of the part of this disturbance that was visible here.

There seems to have been a similar disturbance on October 6, as the photograph taken on that date shows a straight, narrow tail connected at its end with large cloudlike masses.

A very great change in the condition and direction of the tail occurred about September 16. A photograph on that date, through a very thick sky, showed the tail violently curved at a large angle to its normal direction and to the position it had later on September 17.

This comet has forcibly impressed upon us the necessity of testing all comets photographically with a reasonable exposure once or twice during their visibility to see if they are active. I have done this, in a sense, with a number of these bodies, but have essentially found that a comet when faint, like this one at first, does not seem to show evidences of activity or of a tail. Such exposures have usually resulted in adding nothing to the telescopic view. The present comet, had its discovery been a visual one, would not have suggested any promising results from the application of photography, because it was faint visually, and apparently without any or with but little tail. The discovery photograph (made by Professor Morehouse) showed, however, that the comet was really a very active one. This led to its being followed faithfully with the photographic plate. It is indeed remarkable how strongly photographic this comet has proved to be. Until recently it has been a rather faint object in the 5-inch guiding telescope of the Bruce, especially so when the guiding wires, with the smallest possible illumination, have been placed over it; yet at the same time that portion which could be seen at all, readily photographed in a few minutes, and a longer exposure brought out features that could never have been suspected visually.

One fact that is specially emphasized by these pictures with the different lenses is, that what we might, with a long exposure, take to be a picture of the comet may be only a composite made up of the various forms it has assumed during the exposure. In one or more cases the exposure with the 3-inch lens has been carried forward over several exposures with the other lenses. The result is a considerably different looking comet in the several pictures. Of course this is not so true when the comet is changing slowly.

As is known, the Bruce telescope of the Yerkes Observatory consists of two portrait lenses of 10 and $6\frac{1}{4}$ inches aperture. These are bound rigidly together along with a 5-inch guiding telescope. There is also attached to it, in a wooden box, a third lens of $3\frac{4}{10}$ inches diameter. All three lenses have been used in the work on the comet with great success. The smaller lens, while showing practically everything obtained with the larger ones but on a smaller scale, gave the full extent of the tail, which sometimes extended beyond the edges of the larger plates.

For the benefit of those interested in the comet the following table contains a list of the photographs which I have thus far secured. It has been photographed on every possible occasion, and will be followed as long as photographs can be made of it from this latitude.

The short exposures have been through breaks in clouds or in moonlight. Altogether about 190 negatives have been made of the comet with the three lenses.

There will be a great deal of material in these photographs, and in others taken elsewhere, for determining the motion of the particles of the tail. It is very evident, however, that this must be used with great caution or it may lead to erroneous conclusions. The very conditions favorable for determining the motion, i. e., definite masses receding from the comet, are apparently adverse to a determination of the true motion of the average particles whose outward

Central Standard Time	10-Inch		6-Inch		3.4-Inch	
	Middle of Exposure	Duration	Middle of Exposure	Duration	Middle of Exposure	Duration
1908						
Sept. 2......	11^{h} 42^{m}	2^{h} 0^{m}	11^{h} 42^{m}	2^{h} 0^{m}	11^{h} 42^{m}	2^{h} 0^{m}
3......	13 35	3 45	13 35	3 45	13 35	3 45
3......	16 4	0 22	16 4	0 22		
5......	14 47	2 46	14 47	2 46		
6......	14 44	2 40	14 44	2 40	14 44	2 40
7......	15 14	1 48	15 14	1 48	15 14	1 48
8......	16 6	2 3	16 6	2 3	16 6	2 3
12......			8 4	0 18		
16......	9 35	1 55	9 35	1 55	9 35	1 55
17......	10 15	2 30	10 15	2 30		
18	9 37	3 17	9 37	3 17	9 37	3 17
19......	9 51	4 7	9 51	4 7	9 51	4 7
20......	12 38	1 6	12 38	1 6		
21......	11 16	3 37	10 28	2 0	11 21	3 47
21......			12 20	1 30		
21......	14 25	1 40	14 25	1 40	14 25	1 40
23......	9 58	3 32	9 7	1 50	9 24	2 25
23......			11 2	1 25		
24......			8 0	0 55	8 0	0 55
25......	9 6	4 7	8 2	2 0	9 6	4 7
25......			10 9	2 0		
25.	13 43	2 18	13 43	2 18		
26......	9 3	4 12	7 57	2 0	9 0	4 0
26......	12 14	1 25	12 14	1 25		
29......	10 40	2 20	10 45	2 30	10 40	2 20
30......	11 46	3 0	11 16	2 0	12 48	5 4
30......	14 22	1 56	13 25	2 0		
30......			14 57	0 47		
Oct. 1......	9 7	4 0	7 37	1 0	8 7	2 0
1......	11 21	2 7	8 43	0 50	13 43	2 5
1......	13 43	2 0	10 48	1 0		
1......			11 55	1 0		
1......			13 15	1 5		
1......			15 0	0 35		
2......	10 51	1 5	7 29	1 2	7 29	1 2
2......	12 28	2 0	10 3	1 30	10 23	2 10
2......	14 59	2 49	11 38	1 30	12 38	2 10
2......			13 16	1 30	15 1	2 46
2......			15 18	2 11		
3......	8 14	1 14	8 11	1 19	11 27	3 8
3......	11 7	2 28	10 45	1 45	11 29	3 8
3......	13 35	2 21	12 43	1 54	14 58	3 35
3......	15 48	1 47	14 38	1 30		
3......			16 8	1 7		
4......	13 5	1 45	13 5	1 45	13 5	1 45
5......	13 40	1 40	13 35	1 35	14 15	2 50
5......	15 37	2 6	15 31	2 18	15 35	2 20
6......	15 58	1 24	15 58	1 24	15 58	1 24
7......	16 10	1 1	16 10	1 1	16 10	1 1
8......	8 2	0 30	8 2	0 30	8 2	0 30
9......	6 43	0 37	6 43	0 37	6 43	0 37
11......	6 42	0 35	6 42	0 35	6 42	0 35
12......	6 50	1 9	6 50	1 9	6 50	1 9

Central Standard Time	10-Inch		6-Inch		3.4-Inch	
	Middle of Exposure	Duration	Middle of Exposure	Duration	Middle of Exposure	Duration
1908						
Oct. 12......	$9^h\ 27^m$	$0^h\ 30^m$	$9^h\ 27^m$	$0^h\ 30^m$	$9^h\ 27^m$	$0^h\ 30^m$
13......	6 50	1 1	6 50	1 1	6 50	1 1
14......	6 52	1 5	6 50	1 0	6 59	1 10
14......	8 4	1 10	8 1	1 15	8 9	1 0
15......	6 58	1 22	6 54	1 15	7 35	2 36
15......	8 31	1 30	8 30	1 33	9 14	0 30
15......	10 58	0 57	10 54	0 49	11 29	2 0
15......	12 2	0 54	12 12	0 54		
15......	13 11	0 33	13 11	0 33		
16......	6 54	1 20	6 54	1 20	6 54	1 20
16......	9 32	2 15	9 32	2 15	9 32	2 15
17......	6 38	0 47	6 38	0 47	6 38	0 47
17......	8 2	0 10	8 2	0 10	10 41	2 10
17......	10 38	2 5	10 38	2 5		
19......	8 38	1 30	8 38	1 30	8 38	1 30
21......	7 10	1 56	7 10	1 56	7 20	2 10
21......	9 19	2 3	9 19	2 3	9 19	2 3
22......	8 2	0 35	8 2	0 35	8 2	0 35
24......	10 33	0 18	10 33	0 18	10 33	0 18

flow forms the tail. It would seem reasonable that these masses would have a much slower speed than the individual particles forming the general stream of the tail. They probably contain particles of greater size and mass which would be less under the influence of the pressure of sunlight, and would, therefore, have a much less outward velocity than the general particles of the tail. Whatever the cause, the fact is that on several occasions these masses have had independent streams or tails issuing from them, like those from the comet itself, where the smaller particles are evidently detached from the mass and forced out with a very much greater velocity. This was also shown in the case of Daniel's comet on July 11, 1907, where a mass left behind was actually moving sunward under the combined influence of gravitation and the initial velocity of its particles when component parts of the head. I have called attention to this peculiarity in the case of Borrelley's comet, where the new tail on July 24, 1903, was moving out more rapidly than the rear portion of the old disconnected tail, which was at that time drifting away from the comet and the sun (*Astrophysical Journal*, **18**, 211, 1903).

An example of secondary tails from receding masses is found on a photograph of Swift's comet on April 7, 1892. (See *Popular Astron-*

omy, **12**, 2, 1904, for a photograph and description of the comet on this date.) Morehouse's comet also presented a similar appearance on October 15.

In a paper "On the Anomalous Tails of Comets" (*Astrophysical Journal*, **22**, 249, 1905) I urged the necessity of employing shorter intervals than a day, to photographically connect the physical changes occurring in an active comet. It was shown that a history from hour to hour was necessary to correctly represent the progress of these changes, for a comet would at times completely transform itself in a day. In that paper attention was also called to the opportunity offered by a comet at a high northern declination for repeated exposures throughout the night. These facts have been more clearly brought out by the present comet. The photographs of it have proved the extraordinary rapidity with which a comet can alter its appearance when in one of its changing moods.

YERKES OBSERVATORY
October 26, 1908

AN ELECTRIC FURNACE FOR SPECTROSCOPIC INVESTIGATIONS, WITH RESULTS FOR THE SPECTRA OF TITANIUM AND VANADIUM[1]

By ARTHUR S. KING

In designing an electric furnace for spectroscopic work in the laboratory of the Mount Wilson Solar Observatory, several requirements were kept in mind.

1. An apparatus which should give a long, uniformly heated column of vapor which might be brought to a temperature not very much below that of the electric arc. This need was shown by preliminary experiments which demonstrated the difficulty of producing by furnace methods the spectra of refractory substances such as titanium and vanadium, highly important in solar investigations.

2. Regulation of the furnace temperature, so that the direct effect of varying temperature might be observed, when other conditions remained unchanged.

3. The control of the conditions surrounding the luminous vapor, to observe the effect of changes in pressure and surrounding atmosphere. If spectra can be produced giving almost as many lines as the arc, the superiority of the furnace is manifest in that the effect of external influences such as pressure may be observed without an accompanying change in the action of the light-source itself, such as must take place in the arc or spark under pressure.

4. The possibility to observe absorption effects given when white light is passed through the highly heated vapor in the furnace.

The development of electric furnace work has shown that the type known as the "tube resistance furnace" is the one best adapted to all of these requirements. The temperature in such a furnace is regulated by the strength of the current passing through a tube, usually of carbon or graphite, supported horizontally and containing the substance to be vaporized. Such a tube must of course be pro-

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 28.

PLATE XXIII

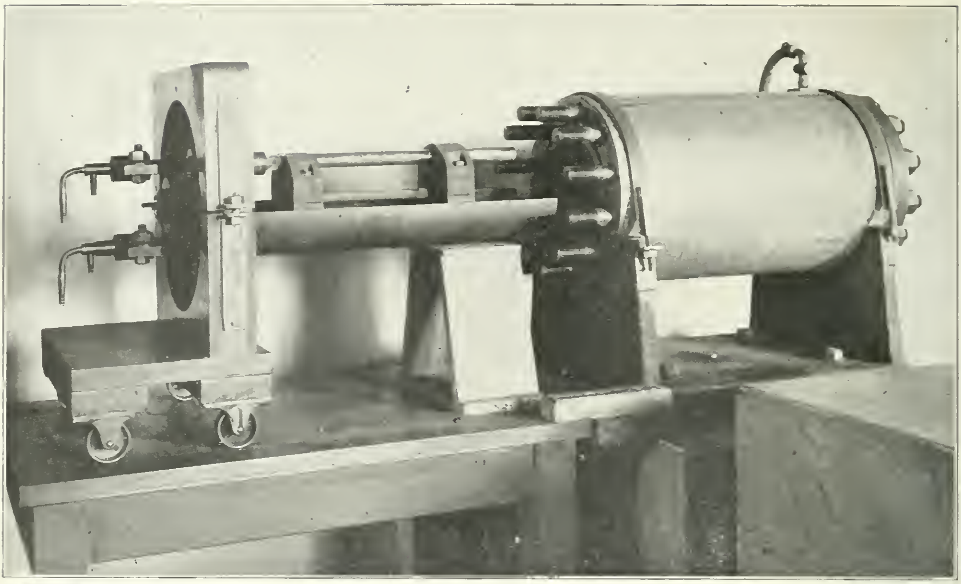

FIG. 1.—ELECTRIC FURNACE OPEN, WITH JACKETING MATERIAL REMOVED

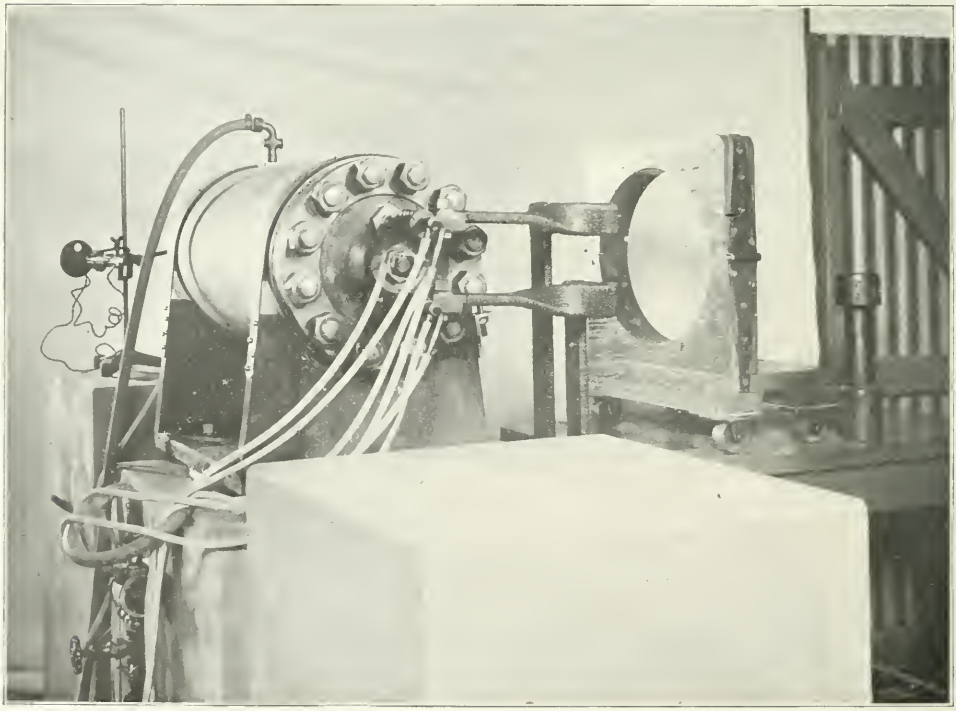

FIG. 2.—ELECTRIC FURNACE CLOSED, IN POSITION

tected from contact with the air, which would cause it to be quickly consumed. The best protection has been found to be a vacuum or a neutral gas around the tube. The inclosure in which the tube is placed for this purpose may be made strong enough to withstand any desired pressure. Such an apparatus, with a regulated current supply to the tube and windows in the walls of the chamber through which the interior of the tube could be observed, would fulfil the several purposes already outlined.

The furnace will be only briefly described in this paper, with a short account of its performance in the first investigation undertaken. The complete description, with detailed drawings, and the full discussion of the results with their bearing on astrophysical problems will be left for a later paper in the *Publications* of the Solar Observatory.

Plan of furnace.—The method adopted for the construction of the furnace was to arrange all of the essential parts in the form of a cartridge attached to one of the heads of a steel chamber, this chamber being built to stand high pressures. The arrangement is clearly shown in the photograph of the open furnace (Plate XXIII, Fig. 1). A half-cylinder of iron, screwed firmly to the head of the pressure chamber, contains two graphite blocks which serve to hold the ends of the horizontal resistance tube and also establish contact between these ends and the copper pipe electrodes which pass through the steel head and carry the electric current. These graphite blocks are each 2 inches thick, about 6 inches wide at the middle, and in three sections. The block for the lower electrode has its top cut low enough to allow the passage of the upper electrode. The blocks are provided with vertical bolts $\frac{3}{8}$ inch in diameter, which hold the sections of the block together and when tightened make firm contact between the copper electrodes and the ends of the resistance tube. Sheets of asbestos or mica under the blocks secure insulation from the iron half-cylinder.

The length of the upper electrode at present employed permits the use of resistance tubes 16 inches long, with 9 inches to be heated between the blocks. Shorter tubes may of course be used by placing the blocks closer together, as contact can be made at any point along the upper electrode. With a longer pipe above, the size of the inclosing chamber would permit the use of a resistance tube about 22 inches long, with 18 inches heated.

The jacketing about the resistance tube for heat insulation is not shown in the photograph. It was found, as has been noted by other workers in this field, that any jacketing material placed in contact with the resistance tube will fuse to some extent and conduct part of the current. The jacketing now in use works well. A carbon tube was made by boring out a rectangular block (round would serve as well) from end to end with a hole ¼ inch larger than the resistance tube to be used. The length was ½ inch less than that of the resistance tube between blocks, the walls no thicker than necessary to secure strength. This tube was split from end to end so that it could be placed around the resistance tube after the latter was in position, giving a free space of about ⅛ inch all around the resistance tube. The space between this carbon protector and the iron half-cylinder was then filled with carborundum powder, a complete jacketing being obtained by heaping the carborundum entirely over the carbon protector, stiff sheets of mica at the sides of the iron half-cylinder enabling this to be done.

Electrodes.—The current is carried to the ends of the resistance tube by two copper pipes passing through the cylinder head in insulated bushings. Each pipe is made of two tubes, one inside the other, of ½ inch and ¾ inch iron pipe size respectively, giving a tube of ⅝ inch I. D. and $1\frac{1}{16}$ inch O. D. This pipe is plugged at the inner end and the water cooling is given by a thin-walled copper tube, supported coaxial with the electrode pipe, carrying water to one inch from the end of the latter, the water then flowing back and bathing the inner wall of the electrode. A heavy copper lug connects the copper pipe outside the cylinder head to a copper bar $\frac{1}{2}\times 2\frac{1}{2}$ inches which passes to the terminals of the cable from the transformer.

Resistance tubes.—The tubes thus far employed have been of either agglomerated carbon or Acheson graphite, in both cases of ½ inch inside diameter and 12 inches long, 1½ inch at each end being clamped in the graphite contact block. The carbon tubes are molded, of $\frac{15}{16}$ inch O. D. These gave good results only after the furnace had been heated two or three times, being allowed to cool and the tube cleaned after each heat. The first heating gave off considerable water vapor, also smoke from the constituents of the binding material of the carbon tube. The latter formed a slag at the ends of the tube, almost closing them, so that nothing further could be done until the chamber was opened and the slag cleared away. A strong impurity spectrum was also given, especially of sodium and aluminum. After the second heat there was much less trouble from these sources, and a number of very satisfactory runs were made with these tubes. A further troublesome feature of the carbon tubes is the fact that after a run at a high temperature, the carbon was thoroughly graphitized, making a considerable change in the resistance of the tubes.

Acheson graphite has given better satisfaction in many respects as a material for tubes. There is no appreciable water vapor given off, no slag formed, the material remains apparently unchanged, and the disturbance from impurities in the graphite is very small. The tubes were bored out and turned to $\frac{23}{32}$ inch O. D.

With both the carbon and graphite tubes, the ends of the tubes and also the holes in the graphite blocks for the tube and for the copper electrodes were thoroughly rubbed with powdered Acheson graphite, grade 1310, which filled the pores of the surfaces and greatly improved the contacts.

Pressure chamber.—The steel chamber to contain the cartridge described in the foregoing is shown in each of the photographs, Figs. 1 and 2, Plate XXIII. The length of the chamber without the heads is 24 inches, the internal diameter 8 inches, the walls having a ruling thickness of $1\frac{1}{2}$ inch, thickened at the ends with flanges 3 inches thick and 2 inches wide. In each of these flanges there are twelve steel bolts of $1\frac{1}{4}$ inch diameter to hold the heads. The head to which the cartridge is attached contains, besides the insulated bushings for the passage of the electrode tubes, a bronze window holder which screws into the center of the head and is provided with a high-pressure glass window in the form of a truncated cone with large end inside, the metal around the window being cooled with a special water jacket. For the work thus far, which has been done with the chamber pumped out, a piece of plate glass has been cemented on the outside of the window holder. The second head has a similar window holder and contains in addition two holes into which fit inlet and outlet pipes for gases and the connections for the high-pressure apparatus. The chamber has been tested to stand a working pressure of 200 atmospheres.

The steel chamber requires efficient water cooling, which is provided for by riveting a cylinder of galvanized sheet iron to the end flanges, allowing the space between them to be filled with water. The water enters below at one end of the jacket and leaves above at the other end.

Current supply.—The current is taken from a 50 K. W. transformer, fed with 2000 volts and giving 5, 10, 20, and 30 volts in the secondary. No regulating resistance is used, the different voltages being used for different temperatures of the furnace, and the voltage is put directly on the furnace tube with as little loss in the connections as possible.

Operation of furnace.—The furnace chamber, whose total weight is over 600 lbs., lies in a rack of cast iron, which rests in turn on the planed ring of an iron plate imbedded in the top of a masonry pier. The rack is centered by a pivot in the bed-plate, and may thus be turned in a horizontal plane to any desired angle. To remove the cartridge from the pressure chamber, the head to which the cartridge is attached is clamped firmly in the carriage shown to the right in the photograph, Plate XXIII, Fig. 2. This is a wooden ring mounted on a base provided with casters. The carriage is then rolled back on a table prepared for it, drawing the head horizontally off the bolts and with it the cartridge. The latter when drawn clear of the chamber is supported by a wooden stand on the table. The graphite blocks, resistance tube, and jacketing material are then placed in position in the open, where all of the parts can easily be put in correct adjustment. The substance to be vaporized is placed in the resistance tube and the cartridge returned to the chamber. The furnace is then turned back into position so that the two windows and the furnace tube in line with them are pointing toward the mirror above the slit of the large Littrow spectrograph,[1] in which position the heavy copper bars from the transformer connections fit into place on the ends of the copper pipe electrodes.

When the furnace is in position, if a run in vacuum is desired, the

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[1] See *Contributions from the Mount Wilson Solar Observatory*, No. 27.

air is removed by means of a Geryk pump, the water is turned on through the several jackets, and the closing of a primary switch causes the current to pass.

Optical arrangement.—As has been noted, the furnace allows the spectrum of the substance vaporized in the resistance tube to be observed to equal advantage from either end. The Littrow grating spectrograph is usually used with the lens at the 13-foot focus. The light passes through a lens to a mirror which reflects it vertically to the slit. An image of the interior of the tube is thus formed on the slit, the middle portion of the length of the tube being in the sharpest focus. The image is made about the same size as the object and the slit is chosen of such length that only the light from the center of the image passes through, the image of the white-hot walls and of any solid matter in the tube being entirely cut out.

The comparison arc for the identification of lines is placed directly back of the furnace so that its light passes through the furnace tube and gives an image slightly out of focus on the slit if the same condensing lens is used. The proper position of the lens for the furnace tube being known, the adjustment of the image of the tube on the slit may be made by means of the light from the arc, so that all is in readiness for an exposure when the furnace is turned on.

The window at the other end of the furnace may be used to photograph with a prism spectrograph on a movable table, enabling a series of short exposures to be made simultaneously with the longer exposures required by the Littrow; or it may be used to watch the condition of the spectrum by means of a direct-vision spectroscope, enabling the exposures to be begun and ended at the proper time. A third use is for temperature measurements with the Wanner pyrometer during the progress of an exposure with the Littrow spectrograph.

Temperature measurements.—A Wanner pyrometer was used to measure the temperature of the hottest part of the furnace tube. This instrument has a Reichsanstalt calibration, and judging by the good agreement of its readings with and without the dark glass, is highly reliable. The measurements so far taken have been for the purpose of showing the temperatures corresponding to a certain voltage used on the furnace when a given tube was employed. Temperature measurements have not been made when a spectrum was being photographed, as the small window in the furnace head does not allow satisfactory temperature measurements to be made without a bright background such as a graphite plug placed in the central part of the tube. For this reason, special runs of the furnace were made for the pyrometer measurements, reproducing as nearly as possible the conditions under which a certain spectrum was observed. These observations have given results sufficiently concordant among themselves to give a reliable value for the approximate temperature corresponding to each voltage on the furnace. Thus with graphite tubes the following measurements were obtained:

Volts	Degrees C.	Number of Observations
5	1700–1800	4
10	2400–2500	4
20	2850–2950	2
30	3015	1

For the carbon tubes a lower series of temperatures was obtained, 1650°, 2570°, and 2770° being found from one set of readings for 10, 20, and 30 volts respectively.

These temperatures were measured for a certain length and size of tube and would of course vary if any of the dimensions were changed. They are given here merely to show the range of temperatures available in the work already done. Each set of observations was made for a different run of the furnace with a different tube, mounted in as nearly the same way as possible. The temperature was taken in each case after the current had passed long enough to bring the tube to a fairly steady condition, attained only after the jacketing material had become highly heated; and at the lower voltages some increase over the above temperatures could be obtained by prolonging the run.

It will be noted that the use of 30 volts does not give a proportional increase in temperature over 20 volts and that the highest temperature obtained with the graphite tube (which would probably have been increased only slightly, if at all, by the use of a still higher voltage) is considerably below the temperature of the positive pole of the carbon arc, measured by Waidner and Burgess[1] with the

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[1] *Bulletin, Bureau of Standards,* Vol. I, pp. 109–124.

Wanner pyrometer as about 3400° C. With the carbon tubes, the graphitizing of the material, which occurred after a short run at 20 volts and thereby lowered the resistance of the tube, was doubtless in some measure responsible for this; but in the case of the graphite tubes the material appears to remain unchanged. In the light of the data thus far obtained, it seems fair to ascribe this condition to the lively vaporization of the carbon (or graphite) which begins at about 2500° C. and becomes so vigorous at 2800° C. that the life of the thin graphite tube is very short when used at 20 and 30 volts. The carbon spectrum was regularly obtained with the graphite tubes at the 10-volt temperature and became very intense at the higher voltages. We have thus conclusive evidence that the vaporizing point of carbon is much below the temperature of the hottest part of the carbon arc, making it probable that the high temperature of the positive terminal is due to a superheating caused by a bombardment of this pole by particles impelled by the electric forces present in the arc.

It has been noted that a graphite plug in the middle of the tube was used when making a pyrometer measurement, in order to provide an incandescent surface at which to direct the instrument. It should give measurements of the same accuracy if the pyrometer were directed at the inner surface of the incandescent tube, and a measurement was made to test this with the bronze window holder removed, giving an opening $1\frac{3}{4}$ inch in diameter in the steel head, which was covered by a piece of plate glass. With this aperture, the pyrometer was directed alternately at the plug and at the adjacent wall of the tube, and the readings were practically the same, showing that the measurements made with the plug in the tube were approximately correct for the wall in the middle portion. When the tube is unobstructed and filled with vapor from any substance placed in it there is of course more or less of a temperature gradient between the wall and the vapor in the center.

SPECTROSCOPIC RESULTS

A series of photographs has been made of the spectra of iron, chromium, titanium, and vanadium with the Littrow spectrograph at its 13-foot focus, using the first order of a plane grating 5 inches

TITANIUM

λ Hasselberg	Intensity Arc	Intensity Furnace	λ Hasselberg	Intensity Arc	Intensity Furnace
4256.18	5	3	4512.88	36	15
4260.91	8	6	4518.18	38	15
4263.28	17	9	4522.97	40	15
4270.30	28	6	4527.48	36	18
4274.73	34	18	4533.42	40	21
4276.55	7	6	4534.97	40	18
4281.49	7	9	4536.25	44	33
4282.85	14	12	4544.83	38	15
4285.15	8	6	4548.93	38	15
4286.15	34	12	4552.62	42	15
4287.55	28	12	4555.64	38	15
4290.07	31	12	4558.28	3	6
4291.32	28	15	4563.60	34	12
4294.28	22	9	4590.11	6	6
4295.91	28	12	4617.41	40	15
4298.82	36	18	4623.24	34	15
4302.08	38	21	4629.47	17	15
4306.07	38	21	4639.83	34	24
4308.64	34	9	4645.36	10	12
4314.95	36	18	4650.16	8	9
4318.83	13	9	4656.60	36	18
4321.82	8	6	4667.76	38	18
4325.30	8	9	4675.27	6	15
4379.40	6	18	4682.08	39	21
4384.85	36	12	4691.50	19	15
4394.04	9	3	4698.94	18	15
4395.17	36	15	4710.34	12	18
4399.92	9	3	4715.46	3	18
4404.42	26	15	4723.32	6	12
4414.29	10	12	4731.33	4	9
4417.88	15	9	4742.94	13	6
4421.92	7	12	4758.30	24	9
4423.00	8	15	4759.44	26	12
4426.24	9	15	4778.44	5	3
4427.28	38	18	4781.91	4	12
4430.19	7	9	4792.65	5	3
4434.15	14	15	4799.95	6	6
4436.75	5	6	4805.25	8	9
4440.49	9	6	4820.56	10	15
4443.97	38	12	4841.00	22	15
4449.32	36	15	4848.62	3	6
4451.07	30	12	4856.18	12	9
4453.48	38	18	4868.44	8	9
4455.48	36	15	4870.28	10	12
4457.59	40	21	4885.25	15	15
4463.70	9	12	4900.08	14	12
4465.96	20	12	4913.76	10	15
4471.40	22	15	4419.99	2	6
4475.00	8	12	4921.90	4	9
4480.72	8	3	4928.50	3	9
4481.41	35	12	4973.25	2	6
4482.84	8	9	4975.52	3	9
4489.24	19	9	4978.39	3	9
4496.33	22	18	4981.91	40	21

TITANIUM—*Continued*

λ Hasselberg	Intensity Arc	Intensity Furnace	λ Hasselberg	Intensity Arc	Intensity Furnace
4989.33	3	9	5210.55	40	30
4991.24	40	21	5219.88	4	21
4997.26	3	15	5224.71	8	18
4999.67	40	21	5238.77	3	18
5001.16	5	12	5246.75	1	9
5007.42	38	18	5251.14	4	18
5009.81	2	15	5266.20	6	18
5013.45	5	9	5283.63	6	9
5014.40	40	21	5295.95	5	15
5016.32	14	18	5297.42	5	9
5020.17	20	18	5298.61	3	12
5023.02	18	18	5369.81	7	18
5025.00	15	15	5397.28	8	24
5036.10 }	20	12	5404.25	5	18
5036.65 }			5409.81	8	24
5038.55	16	12	5426.48	2	24
5040.12	24	15	5429.37	4	21
5043.77	2	15	5436.93	2	12
5045.58	2	18	5438.53	2	9
5053.06	2	12	5446.80	7	27
5064.82	30	21	5449.40	4	6
5087.24	3	15	5453.88	7	24
5113.64	4	15	5460.72	7	24
5120.60	7	12	5471.43	6	12
5145.62	8	15	5474.43	9	18
5147.63	7	21	5477.92	12	15
5152.36	6	21	5481.64	10	21
5173.94	34	27	5488.44	8	12
5193.15	39	27	5490.38	16	21
5194.25	2	6	5504.10	14	9
5206.30	8	21	5512.72	38	27
5208.08	8	18	5514.58	40	42

VANADIUM

λ Hasselberg	Intensity Arc	Intensity Furnace	λ Hasselberg	Intensity Arc	Intensity Furnace
4090.70	38	15	4128.25	44	18
4092.83	42	15	4132.13	43	18
4095.64	32	15	4134.61	42	18
4099.93	33	12	4143.02	9	12
4102.32	26	15	4160.57	11	15
4105.32	42	15	4180.99	26	21
4109.94	42	15	4183.59	11	12
4111.92	44	18	4191.70	14	15
4113.65	9	6	4194.17	12	15
4115.32	42	15	4209.98	15	21
4116.64	40	24	4216.52	21	15
4119.58	15	6	4232.62	16	9
4121.13	9	6	4234.12	14	15
4123.65	44	15	4235.90	8	6

VANADIUM—*Continued*

λ Hasselberg	Intensity Arc	Intensity Furnace	λ Hasselberg	Intensity Arc	Intensity Furnace
4251.45	6	9	4469.88	40	15
4257.53	5	6	4474.89	26	15
4259.46	6	15	4480.20	8	18
4265.28	5	6	4489.06	42	24
4268.78	40	15	4491.35	10	3
4271.71	40	15	4496.26	11	27
4277.12	35	9	4502.12	15	15
4283.06	4	9	4506.41	6	6
4284.19	34	12	4514.36	9	3
4286.57	5	15	4517.77	5	27
4287.97	4	15	4524.38	21	6
4291.97	23	18	4529.47	16	6
4293.25	3	9	4530.97	6	6
4296.28	19	18	4537.84	6	3
4306.35	22	27	4540.18	6	9
4307.33	20	15	4545.57	42	12
4309.95	22	27	4552.05	4	24
4330.18	42	24	4554.21	6	24
4332.98	41	21	4560.90	38	12
4341.15	43	24	4570.60	7	6
4353.02	44	27	4571.96	35	12
4356.10	13	21	4577.36	42	33
4363.48	6	15	4579.38	5	9
4368.25	19	18	4580.57	42	30
4379.38	48	39	4586.54	43	45
4384.07	42	6	4591.39	17	6
4384.87	45	33	4594.27	44	48
4390.13	47	30	4600.34	3	3
4392.24	8	18	4606.33	18	27
4395.40	44	30	4607.40	2	6
4400.74	43	24	4611.10	5	9
4405.20	30	15	4619.97	38	27
4406.80	45	24	4624.62	10	18
4407.85	44	21	4626.67	9	15
4408.36	44	33	4635.35	16	36
4412.30	18	24	4640.25	8	21
4416.63	42	27	4640.92	6	12
4420.08	19	21	4646.59	17	21
4421.73	41	27	4666.33	4	24
4423.41	10	15	4670.66	26	21
4426.17	42	39	4684.64	3	6
4428.68	40	24	4687.10	5	15
4429.95	32	33	4710.74	9	24
4434.80	11	6	4717.85	7	9
4436.31	42	27	4721.70	6	9
4438.02	40	30	4723.06	7	9
4441.88	44	30	4742.79	4	6
4444.40	42	27	4766.80	8	6
4449.77	8	15	4776.54	14	9
4452.19	40	21	4784.65	3	15
4457.65	43	42	4786.70	12	6
4459.93	48	36	4793.10	2	3
4460.46			4797.07	15	6
4462.56	41	18	4799.94	4	15

VANADIUM—*Continued*

λ Hasselberg	Intensity Arc	Intensity Furnace	λ Hasselberg	Intensity Arc	Intensity Furnace
4807.70	18	6	5128.71	5	18
4827.62	28	30	5138.58	4	9
4832.59	26	24	5139.74	3	9
4833.17	26	21	5148.95	3	21
4851.65	40	27	5159.56	3	15
4864.93	39	21	5193.18	6	21
4875.66	41	21	5195.01	7	6
4881.75	42	24	5234.31	7	6
4891.81	3	9	5402.17	12	6
4900.84	4	9	5415.51	17	6
4904.59	7	6	5418.33	3	9
4925.83	5	6	5434.43	6	18
4932.24	2	6	5437.93	2	9
5014.83	3	18	5443.50	1	30
5064.83	2	9	5488.18	17	12
5105.37	6	6	5490.22	5	18

in length with 14,438 lines to the inch. The iron spectrum has been photographed for the region from λ 3700 to λ 6700. The plates thus far taken for the other substances extend only from λ 4000 to λ 5500. Each spectrum was obtained for at least two different temperatures, an exposure being made first with a low voltage on the furnace and then another with a higher voltage, the current being broken for only a few seconds, so that the higher voltage started with the tube and jacketing highly heated from the previous run, and the second exposure was made after a much higher temperature had been established. The exposure times varied with the substance, temperature, and region of spectrum, from one minute at the highest temperatures to 30 minutes for a spectrum barely visible in the direct-vision spectroscope. Ten minutes were usually ample for any spectrum at 2500° C. or higher. The change of temperature during these exposures was not large, and could be kept nearly constant when desired by watching selected parts of the spectrum, especially the carbon flutings, in the visual spectroscope and breaking the current for a few seconds when these became too bright.

It is not the purpose of the present paper to discuss the effects of different temperatures upon spectra; so that in the foregoing tables only a comparison of the arc and furnace spectra of titanium and vanadium is given, with the object of showing the richness of the furnace spectra as compared with the arc and to give a general view of the relative intensities of lines in the two sources, as these spectra have not heretofore been obtained, to the writer's knowledge, by non-electrical methods. These furnace spectra were among the first photographed and were obtained with carbon tubes at about 2700°–2800° C. The arc spectrum was obtained on the same kind of plate (Cramer Isochromatic) with all optical arrangements the same.

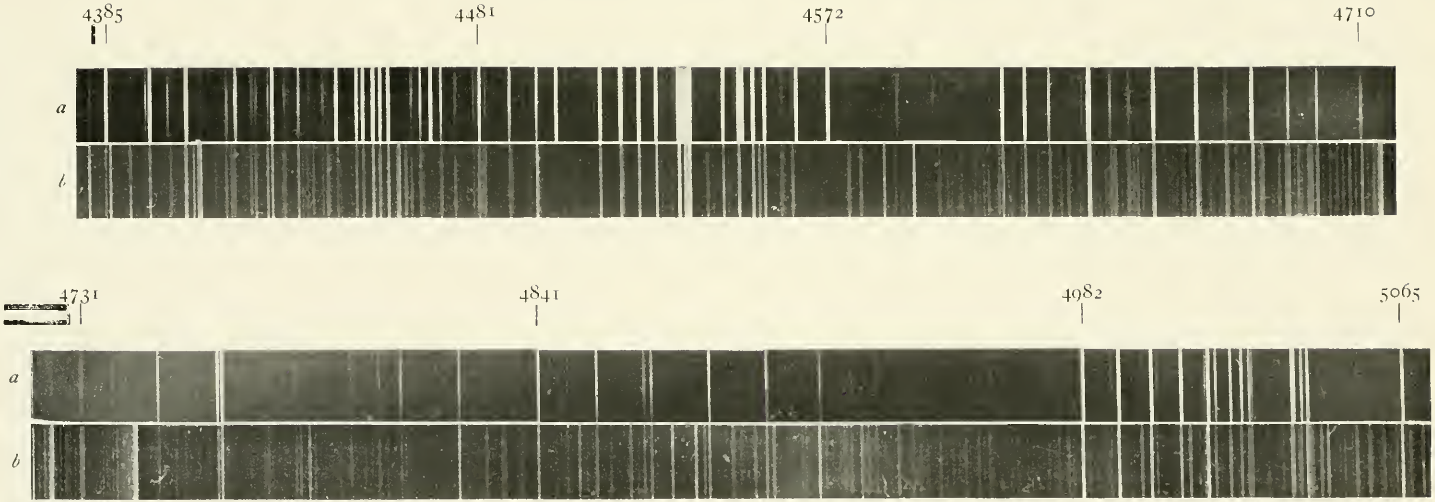
The intensities of lines for both arc and furnace spectra were measured by means of a photographic scale made with the Littrow spectrograph by illuminating the slit with a constant voltage incandescent lamp and photographing the direct reflection from the grating with exposures ranging from 1 to 40. This gave a fairly satisfactory scale as regards gradation in blackness. The change in width of the lines of the scale with exposure time was also measured and a curve plotted to show this variation. This scale was placed in a special holder on a Zeiss spectrocomparator, so that when a spectrum plate was mounted on the moving carriage any line of the spectrum could be brought into the field of the eyepiece opposite the lines of the scale, giving, except for overexposed and reversed lines, a good measure of the intensity by selecting the line of the scale having the same blackness as the spectrum line. If the spectrum line was widened, this was considered in the final estimate of its intensity. Lines of intensity greater than 40 were estimated as closely as possible by extrapolation.

After the tables for arc and furnace were prepared, all of the intensities of furnace lines were multiplied by 3, which gave the spectrum as a whole about the same strength as that of the arc and rendered the relative differences more distinct. Although this proceeding is open to objection from the photometric point of view, it serves well for the rough comparison aimed at in these tables, where the differences in intensity are usually large.

Photographs of the arc and furnace spectra are reproduced in Plates XXIV and XXV for a part of the region covered by the tables of titanium and vanadium lines. Each furnace spectrum shows the spectrum of the other element as an impurity. These photographs, considered in connection with the tables, offer material which may be discussed under the following heads:

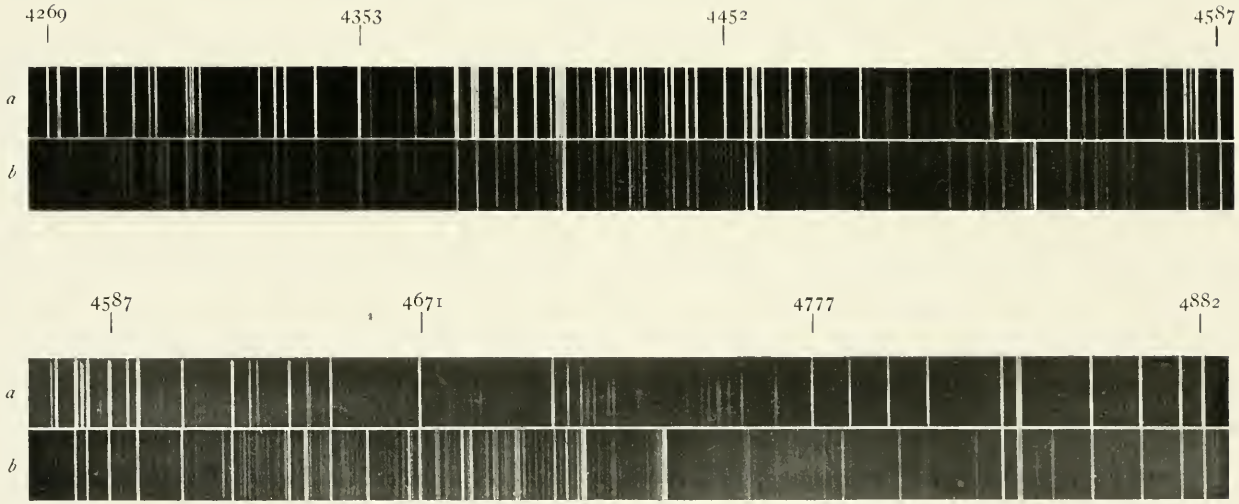
1. The question of temperature radiation. There is nothing to

PLATE XXIV



Spectrum of Titanium
(*a*) In Carbon Arc; (*b*) In Electric Furnace

PLATE XXV



Spectrum of Vanadium
(*a*) In Carbon Arc; (*b*) In Electric Furnace

indicate that temperature was not the sole and sufficient agent in producing these spectra. Electrical action, other than the ionization at a heated surface, was entirely excluded, no arc of any sort being present. As to chemical action, the small residue of air in the pumped-out chamber should have had its oxygen consumed long before the metal in the tube reached its vaporizing point, and if this were not the case, it is scarcely conceivable that enough could have reached the substance at the middle of the white-hot tube to give the vigorous radiation observed as long as a trace of the metal remained. To be sure, some impurities are contained in the material of the carbon tubes; but the tubes of Acheson graphite, containing extremely little foreign matter, were fully as efficient in giving the spectra of the substances placed in them. The spectroscopic evidence on this point is the fact that titanium gives a pure line spectrum, with no trace of the flutings given in the flame of the arc burning in air and generally ascribed to the oxide.

2. The number of lines given by the furnace as compared to the arc. For titanium the rather strong arc photograph gives 31 lines of intensity 3 or higher (1 indicating a line barely visible on the plate) which do not appear on the furnace plate for this region (λ 4250 to λ 5500), the furnace plate thus showing 85 per cent. of the arc lines. For vanadium, the number is relatively smaller, 73 per cent. of the arc lines being given by the furnace from λ 4100 to λ 5500. Longer exposure with the furnace would doubtless have brought out more of the weak lines, as none of the furnace lines attained maximum intensity.

3. The temperatures at which the carbon flutings appear and reach high intensity have been given. The band at λ 4737 may be seen in the reproductions of both the titanium and vanadium furnace spectra. This and the band at λ 5165 are easily obtained of considerable intensity. The cyanogen bands at λ 3883 and λ 4216 also appear, but faintly on account of the small supply of nitrogen.

4. Mention may be made here of the behavior of the "enhanced lines," those given relatively strong in the electric spark as compared to the arc. Eleven of the enhanced lines of titanium given by H. M. Reese[1] appear in the table of titanium furnace lines, and with one exception

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[1] *Astrophysical Journal*, 19, 322, 1904.

are relatively much weaker in the furnace that in the arc. Five enhanced lines are among the 31 arc lines not found on the furnace plate, the two strongest in this list, λ 4501.43 and λ 4572.15, being given by Reese as enhanced in the ratio 9 to 5. A full consideration of this interesting point, together with a study of the enhanced lines of iron, will be given when tables showing the effects of different furnace temperatures upon the several spectra are published.

5. An examination of the tables for both vanadium and titanium shows that generally the lines of shorter wave-length are much stronger in the arc than in the furnace; while in the green region the furnace lines are as a rule relatively stronger. As these lists of intensities for arc and furnace were made up quite independently, the showing made when they are placed side by side is striking evidence of a shift of maximum in the spectrum due to a temperature difference in the two sources.

Mount Wilson Solar Observatory
August 20, 1908

ON THE PROBABLE EXISTENCE OF A MAGNETIC FIELD IN SUN-SPOTS[1]

By GEORGE E. HALE

The discovery of vortices surrounding sun-spots, which resulted from the use of the hydrogen line *Ha*, for solar photography with spectroheliograph,[2] disclosed possibilities of research not previously foreseen. Photographs taken daily on Mount Wilson with this line suggest that all sun-spots are vortices, and provide material for a discussion of spot theories which will soon be undertaken. Revealing, as they do, the existence of definite currents and whirls in the solar atmosphere, they afford the requisite means of testing the operation in the sun of certain physical laws previously applied only to terrestrial phenomena. The present paper describes an attempt to enter one of the new fields of research opened by this recent work with the spectroheliograph.

ELECTRIC CONVECTION

In 1876 Rowland discovered that an electrically charged ebonite disk, when set into rapid rotation, produced a magnetic field, capable of deflecting a magnetic needle suspended just above the disk.[3] It thus appeared, in accordance with Maxwell's anticipation, that a rapidly moving charged body gives rise to just such effects as are caused by an electric current flowing through a wire. Rowland's whirling disk therefore corresponds to a wire helix, within which a magnetic field is produced when a current is passed through it.

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 30. A preliminary note bearing the title, "Solar Vortices and the Zeeman Effect," was sent to *Nature* for publication June 30. A brief abstract of this note appeared in *Nature* for August 20, together with a very interesting paper by Professor Zeeman, who was kind enough to examine some copies of my photographs, taken with the rhomb and Nicol in June. My own note was subsequently printed in *Publications of the Astronomical Society of the Pacific*, **20**, 220, 1908.

[2] Hale, "Solar Vortices," *Contributions from the Mount Wilson Solar Observatory*, No. 26; *Astrophysical Journal*, **28**, 100, 1908.

[3] Rowland, "On the Magnetic Effect of Electric Convection," *American Journal of Science* (3), **15**, 30, 1878.

Recent studies of the discharge of electricity in gases prove that gases and vapors, when ionized by one of several means, contain electrically charged particles. Moreover, at high temperatures carbon and many other elements which occur in the sun emit negatively charged corpuscles in great numbers; the complementary positively charged particles must also be present, more or less completely separated from the negative corpuscles.[1] Thus electromagnetic disturbances on a vast scale may result from the rapid motions of charged particles produced by eruptions or other solar disturbances.

Soon after the discovery of the vortices associated with sun-spots, it occurred to me that if a preponderance of positive or negative ions or corpuscles could be supposed to exist in the rapidly revolving gases, a magnetic field, analogous to that observed by Rowland in the laboratory, should be the result. An equal number of positive and negative ions, when whirled in a vortex, would produce no resultant field,[2] since the effect of the positive charges would exactly offset that of the negative charges. But Thomson's statement regarding the possible copious emission of corpuscles by the photosphere, and the tendency of negative ions to separate themselves, by their greater velocity, from positive ions, led to the belief that the conditions necessary for the production of a magnetic field might be realized in the solar vortices.

Thanks to Zeeman's discovery of the effect of magnetism on radiation it appeared that the detection of such a magnetic field should offer no great difficulty, provided it were sufficiently intense. When a luminous vapor is placed between the poles of a powerful magnet the lines of its spectrum, if observed along the lines of force, appear in most cases as doublets, having components circularly polarized in opposite directions. The distance between the components of a given doublet is directly proportional to the strength of the field. As different lines in the spectrum of the same element are affected in different degree, it follows that in a field of moderate strength many of the lines may be simply widened, while others, which are exceptionally sensitive, may be separated into doublets.

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[1] J. J. Thomson, *Conduction of Electricity through Gases,* p. 165.

[2] Unless separated by centrifugal force, as suggested by Professor Nichols.

THE SUN-SPOT SPECTRUM

It has long been known that the spectrum of a sun-spot differs from the ordinary solar spectrum in several particulars. If, for example, we examine the iron lines in a spot, we find that some of them are more intense than in the solar spectrum, while others are weaker. Again, we perceive that many of the spot lines are widened, and that the degree of widening varies for different lines. Finally, if the observations are made with an instrument of high dispersion, it will be seen that some of the iron lines, which are single in the solar spectrum, are double in the spot spectrum. Such double lines were first seen by Young in 1892 with a large spectroscope attached to the 23-inch Princeton refractor. Walter M. Mitchell, who subsequently observed them with the same instrument, described the doublets as "reversals," which they closely resemble. Mitchell's papers contain a valuable series of observations of these "reversals" and other sun-spot phenomena.[1]

Our previous investigations in this field on Mount Wilson may be summarized as follows:

1. The application of photography to the study of sun-spot spectra. A Littrow or auto-collimating spectrograph of 18 feet (5.5 m) focal length, used with the Snow telescope, gave good results, and permitted a great number of spot lines and bands, not previously known, to be recorded.[2] On the completion of the tower telescope last autumn, these observations were continued with a vertical spectrograph of 30 feet (9.1 m) focal length.[3] Although the only grating available for work in the higher orders is a 4-inch (10 cm) Rowland, having 14,438 lines to the inch (567 to the mm), employed in my experiments in photographing sun-spot spectra at the Kenwood and Yerkes

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[1] Walter M. Mitchell, "Reversals in the Spectra of Sun-Spots," *Astrophysical Journal*, **19**, 357, 1904; "Researches in the Sun-Spot Spectrum, Region F to *a*," *ibid.*, **22**, 4, 1905; "Results of Solar Observations at Princeton, 1905–1906," *ibid.*, **24**, 78, 1906.

[2] Hale and Adams, "Photographic Observations of the Spectra of Sun-Spots," *Contributions from the Mount Wilson Solar Observatory*, No. 5; *Astrophysical Journal*, **23**, 11, 1906.

[3] Hale, "The Tower Telescope of the Mount Wilson Solar Observatory," *Contributions from the Mount Wilson Solar Observatory*, No. 23; *Astrophysical Journal*, **27**, 204, 1908.

Observatories,[1] the results secured with this instrument are very satisfactory, greatly surpassing those obtained with the 18-foot spectrograph. They give the first photographic records of the "reversals" or doublets seen visually by Young and Mitchell, and reveal thousands of faint lines beyond the reach of visual observation.

2. The preparation of a photographic map of the sun-spot spectrum and a catalogue of all the lines. A preliminary map, consisting of 26 sections of 100 Ångströms each, covering the region λ 4600–7200, was prepared last year by Mr. Ellerman from negatives made with the 18-foot spectrograph, and supplied to visual observers taking part in the sun-spot work of the International Solar Union. A much better map, to be made from negatives obtained with the tower telescope and 30-foot spectrograph, will be ready, it is hoped, within a year. The catalogue of lines, which involves a great amount of measurement for the determination of wave-lengths, is well advanced, and one section has been published by Mr. Adams.[2]

3. The identification of the numerous lines which constitute the flutings in the spot spectrum. Photographs of the spectra of titanium oxide, magnesium hydride, and calcium hydride,[3] made in our laboratory by Dr. Olmsted, have furnished the material for this purpose. The measurement of the lines in these flutings is well advanced.

4. The interpretation of the change of the relative intensity of lines observed in passing from the solar spectrum to the spot spectrum. Investigations on the spectra of iron, manganese, chromium, titanium, vanadium, and other metals conspicuous in spots, made with the arc, spark, and flame, indicated that this change is due to a reduction of the temperature of the spot vapors.[4] Subsequent work with a new

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[1] Hale, "Solar Research at the Yerkes Observatory," *Astrophysical Journal*, **16**, 211, 1902.

[2] Adams, "Preliminary Catalogue of Lines Affected in Sun-Spots, Region λ 4000 to λ 4500," *Contributions from the Mount Wilson Solar Observatory*, No. 22; *Astrophysical Journal*, **27**, 45, 1908.

[3] Olmsted, "Sun-Spot Bands Which Appear in the Spectrum of a Calcium Arc Burning in the Presence of Hydrogen," *Contributions from the Mount Wilson Solar Observatory*, No. 21; *Astrophysical Journal*, **27**, 66, 1908.

[4] Hale, Adams, and Gale, "Preliminary Paper on the Cause of the Characteristic Phenomena of Sun-Spot Spectra," *Contributions from the Mount Wilson Solar Observatory*, No. 11; *Astrophysical Journal*, **24**, 185, 1906; Hale and Adams, "Second Paper on the Cause of the Characteristic Phenomena of Sun-Spot Spectra," *Contributions from the Mount Wilson Solar Observatory*, No. 15; *Astrophysical Journal*, **25**, 75, 1907.

electric furnace by Dr. King,[1] the details of which have not yet been published, seems to leave little doubt that this explanation is correct. It is supported by the presence in the spot of compounds which appear to be dissociated at the higher temperature outside the spot, and by the resemblance of spot spectra to the spectra of red stars.[2]

While our investigations have thus furnished a plausible explanation of some of the characteristic phenomena of sun-spot spectra, the widening of lines and the presence of doublets are among the remaining peculiarities that demanded consideration. As we have seen, however, these very peculiarities are precisely what would be expected if a magnetic field were present. Prompted by the theoretical considerations outlined above, and encouraged by their apparent agreement with the facts of observation, I decided to test the components of the spot doublets for evidences of circular polarization and to seek for other indications of the Zeeman effect.

METHOD OF OBSERVATION

The tower telescope forms an image of the sun, about 6.7 inches (17 cm) in diameter, on the slit of a vertical spectrograph, of 30 feet focal length. This instrument, to which reference has already been made, stands in a well with concrete walls, the grating being about 26½ feet (8 m) below the surface of the ground. The temperature at the bottom of the well is so constant that exposures of any desired length may be given, without danger of a shift of the lines resulting from expansion or contraction of the grating. A Fresnel rhomb and Nicol prism[3] are mounted above the slit, so that the light of the solar image passes through them. If the doublets in spots are produced by a magnetic field, the light of their components, circularly polarized in opposite directions, should be transformed by the rhomb into two

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[1] King, "An Electric Furnace for Spectroscopic Investigations, with Results for the Spectra of Titanium and Vanadium," *Contributions from the Mount Wilson Solar Observatory*, No. 28; *Astrophysical Journal*, **28**, 300, 1908.

[2] Hale and Adams, "Sun-Spot Lines in the Spectra of Red Stars," *Contributions from the Mount Wilson Solar Observatory*, No. 8; *Astrophysical Journal*, **23**, 400, 1906; Adams, "Sun-Spot Lines in the Spectrum of *Arcturus*," *Contributions from the Mount Wilson Solar Observatory*, No. 12; *Astrophysical Journal*, **24**, 69, 1906.

[3] Obtained for this purpose in 1905, when the idea of searching for the Zeeman effect in sun-spots had already occurred to me. A visual test of the spot lines for plane polarization, made with the 18-foot spectrograph in 1906, before we had photographed the doublets, gave negative results.

plane polarized rays, differing 90° in phase. Thus, in a certain position of the Nicol, the light from the red component should be transmitted and that of the violet component cut off. When rotated 90° in azimuth, the Nicol should transmit the violet component and cut off the red component. Complete extinction of either component is hardly to be expected, because the light from the spot does not, in general, come exactly along the lines of force, and the doublets may therefore exhibit some traces of elliptical polarization. Moreover, the beam of sunlight undergoes two reflections on the silvered surfaces of the coelostat and second mirrors of the tower telescope, where elliptical polarization must again be introduced.[1] By setting the rhomb at the proper angle, the latter effect, which is not very large, can be almost wholly eliminated, but the former may play some part, even when the spot is at the center of the sun.

The light of the spot, after transmission through the rhomb and Nicol, comes to a focus in the plane of the slit. While photographing the spot spectrum the slit is covered except at its central part, where a portion corresponding in length (from 1 to 2 mm) to the diameter of the umbra, receives the light. During the exposure, which may continue from a few minutes to over an hour, the image of the umbra is kept as nearly as possible central on the slit, any irregularities in the motion of the driving-clock being corrected by the observer. As the exposure for the spot spectrum is from five to twenty times as long as for the solar spectrum, it is evident that care must be taken to prevent light from regions outside the spot from entering the slit.

For a comparison spectrum sunlight is used, generally from a point in the solar image a short distance away from the spot, where none of the characteristic spot phenomena appear. During the exposure, that part of the slit which previously received the light of the umbra is covered, and sunlight admitted on either side. The light of the comparison spectrum passes through the rhomb and Nicol, both of which occupy the same positions as in the case of the spot. Care is taken to see that the grating is fully illuminated, both for the spot and comparison spectra, in all positions of the Nicol.

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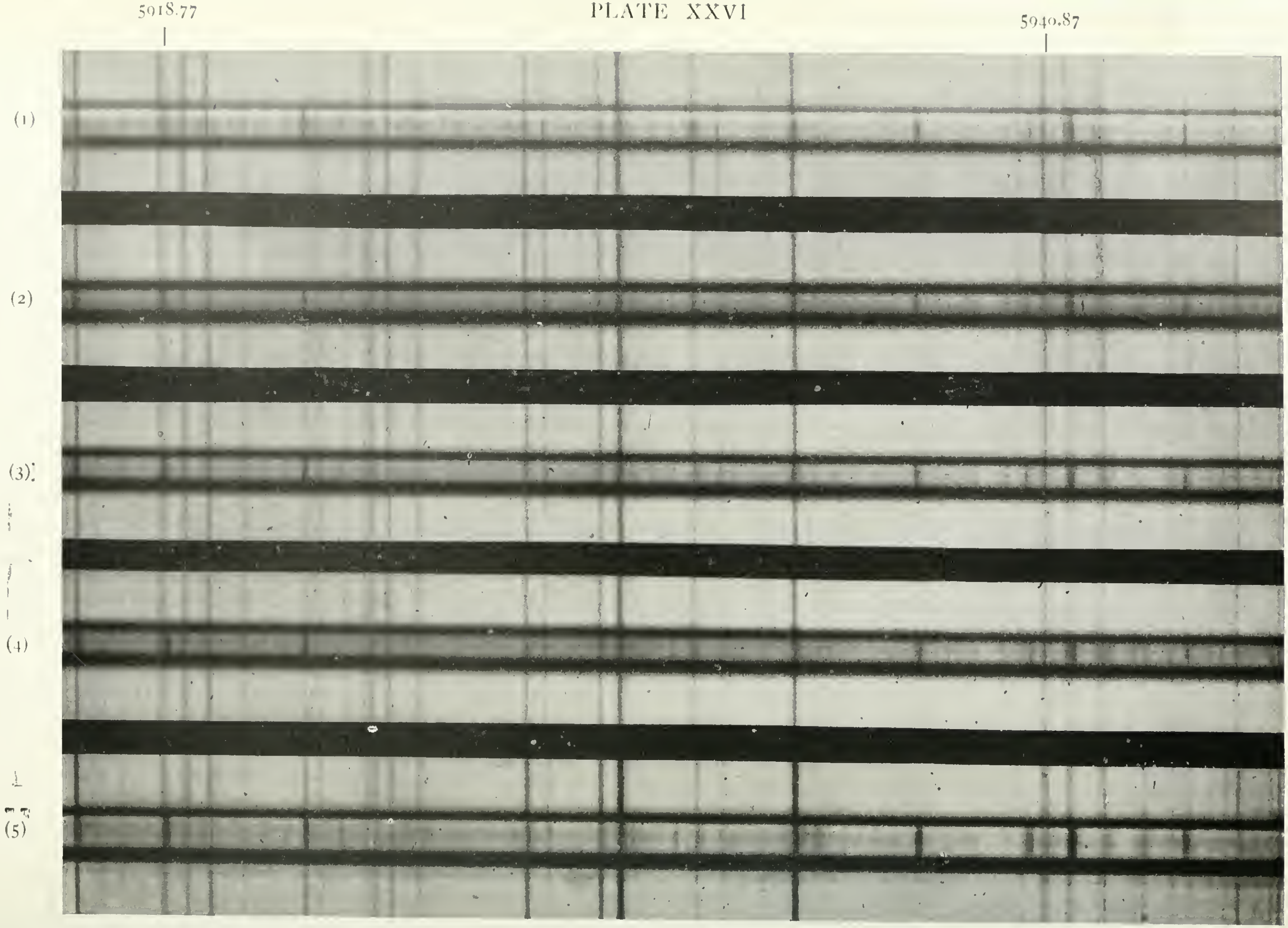
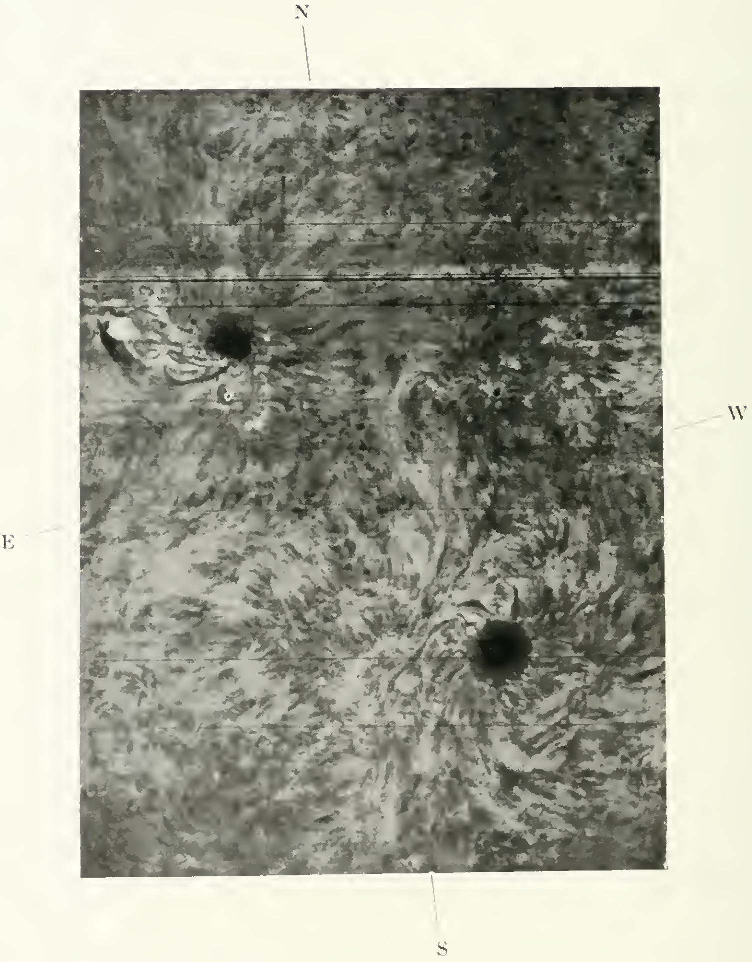
[1] A study of the elliptical polarization of these mirrors has been made by Dr. St. John.

PLATE XXVI



(1) Southern spot, showing red components of doublets. Nicol 29 W. (2) One umbra of northern spot, showing violet components of doublets. Nicol 29° W. (3) Other umbra of northern spot, showing violet components of doublets. Nicol 29° W. (4) Some umbra of northern spot, showing red components of doublets. Nicol 61° E. (5) Spot spectrum without rhomb or Nicol, showing both components of doublets. Scale: 1 Ångström=6 mm.

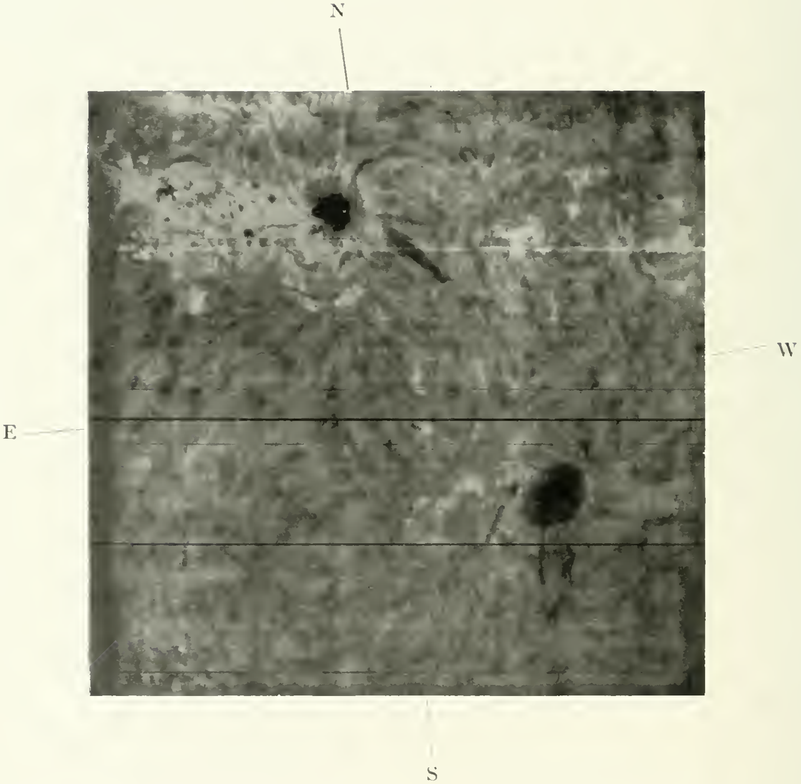
PLATE XXVII



SUN-SPOTS AND HYDROGEN FLOCCULI, SHOWING RIGHT- AND LEFT-HANDED VORTICES

1908. September 9, $6^h\ 20^m$ A. M. Scale: Sun's Diameter=0.3 Meter

PLATE XXVIII



SUN-SPOTS AND HYDROGEN FLOCCULI, SHOWING RIGHT- AND LEFT-HANDED VORTICES

1908, September 7, 6^h 20^m A. M. Scale: Sun's Diameter=0.3 Meter

CIRCULAR POLARIZATION ALONG THE LINES OF FORCE

My first observations were made on June 24, in the second order of the grating, but the results were not conclusive. On June 25 I obtained some good photographs, in the third order, of the region λ 6000–6200, using Seed's "Process" plates, sensitized for the red by Wallace's three-dye formula.[1] These clearly showed a reversal of the relative intensities of the components of spot doublets when the Nicol was turned through an angle of 90°. Moreover, many of the widened lines were shifted in position by rotation of the Nicol, indicating that light from the edges of these lines is circularly polarized in opposite directions. The displacements of the widened lines appeared to be precisely similar in character to those detected by Zeeman in his first observations of radiation in a magnetic field.

A series of photographs, made with the Nicol set at various angles, soon showed the two positions giving the maximum effect. At these positions the weaker components of the strongest doublets are not always completely cut off, but their intensities are greatly reduced. Sometimes hardly a trace of the weaker component remains, as may be seen in the case of the vanadium doublet at λ 5940.87 (Plate XXVI). In this plate No. 5 shows the doublet in the ordinary spot spectrum, photographed without the rhomb and Nicol. No. 4, from a photograph (T 190) made with the Nicol set at 61° E., shows only the red component of the doublet. No. 3 illustrates the effect of turning the Nicol 90°: only the violet component remains. Other spot lines in these photographs change in a similar way.

Photographs like these seemed to leave no doubt that the components of the spot doublets are circularly polarized in opposite directions. Since the only known means of transforming a single line into such a doublet is a strong magnetic field, it appeared probable that a sun-spot contains such a field, and that the widening and doubling of the lines in the spot spectrum result from this cause. But much remained to be done before the proof could be regarded as complete.

In the first place, it was necessary to make sure that the displacement of the lines other than doublets was not due to instrumental causes, such as a change in the illumination of the grating produced by rotating the Nicol. As already stated, care was always taken to

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[1] *Astrophysical Journal*, 26, 299, 1907.

see that the ruled surface was filled with light before making an exposure. Moreover, the magnitude of the displacement was much greater for some lines than for others, and the fact that the shifts were determined with respect to lines of the solar spectrum, whose light had traversed almost the same path as that of the spot in rhomb and Nicol, seemed to leave little room for doubt as to their true character. However, a rigorous test could be applied. The spot spectrum, as well as the solar comparison spectrum, is crossed by lines due to the absorption of water vapor and other gases in the earth's atmosphere. If a change of illumination due to the rotation of the Nicol were concerned, these lines should be displaced from their normal positions. But no such shifts were observed. Furthermore, it is known that the lines of most flutings are not affected by a magnetic field. Accordingly, the cyanogen fluting at λ 3883 was photographed in the spot spectrum, with the Nicol set in two positions 90° apart. Three lines in this fluting, which I have measured on negative T 132, made in the fourth order, show a mean displacement of 0.0004 Ångströms, with respect to the corresponding lines of the solar comparison spectrum. This quantity is well within the error of measurement.[1] We may therefore conclude that the Nicol displaces only those lines which show polarization phenomena.

While measuring this plate, and others taken in the more refrangible part of the spot spectrum, it was found that few of the lines in this region show large shifts. A group of doublets was encountered near λ 4400, the components of which are circularly polarized in opposite directions. In general, however, the shifts produced by rotating the Nicol decrease from the red toward the violet end of the spectrum.

Since this preliminary work I have made over two hundred photographs of spot spectra with polarizing apparatus before the slit. In addition to this collection of plates, numerous photographs of spot spectra, some taken with polarizing apparatus by Dr. St. John, and others made without Nicol or rhomb by Mr. Adams and myself, are available for study. These have been used for the investigation described in the following pages.

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[1] The head and several lines of the titanium oxide fluting at λ 5598, which have since been measured by Mr. Adams, also show no displacement when the Nicol is rotated.

REVERSED POLARITIES OF RIGHT- AND LEFT-HANDED VORTICES

A second test, which also bears upon the hypothesis that the field is produced by the revolution of electrically charged particles in the spot-vortex, may now be described. If a Nicol is set so as to cut off the violet component of a doublet observed along the lines of force of a magnetic field, reversal of the current will cause the red component to disappear and the violet component to become visible. Reversal of the direction of the current in a magnet corresponds to reversal of the direction of revolution in a solar vortex. If it could be shown, by an independent method, that in two sun-spot vortices the charged particles are revolving in opposite directions, the red components of the doublets should appear in the spectrum of one spot, and the violet components in that of the other, the position of the rhomb and Nicol remaining unchanged.

Fortunately the spectroheliograph plates indicate the direction of revolution in the solar vortices. The vortices are constantly changing in appearance, and the stream lines are not always clearly defined. Plates XXVII and XXVIII are reproduced from photographs of the sun made by Mr. Ellerman with the 5-foot spectroheliograph on September 9 and 10. They show two spots, one in the northern, the other in the southern hemisphere, with vortices indicating revolution in opposite directions, if we may judge from the curvature of the stream lines.[1] Portions of the spectra of these spots, photographed by myself on September 9, are reproduced in Plate XXVI. No. 1 shows the spectrum of the southern spot, in which the direction of revolution was clockwise, taken with the Nicol set at 29° W. Only the red components of the doublets appear. The northern spot, in which the revolution was counter-clockwise, was then photographed (2). Although the Nicol and rhomb remained in the same position as before, the red components of the doublets are now cut off, while the violet ones are visible. During this exposure the slit was kept on the western umbra of the northern spot, which was divided into two parts by a bridge (not shown in the reproductions). Another exposure, with Nicol and rhomb as before, was then made on the eastern umbra of the same spot (3), with results similar to those obtained for the western umbra. For the final exposure (4) the slit was kept on the eastern

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[1] Right- and left-handed vortices have also been found in the same hemisphere.

umbra of the northern spot, and the Nicol rotated 90°. As was to be expected, the red components were brought into view, and the violet components extinguished. This spectrum is therefore precisely similar to that of the southern spot, which was taken with the Nicol in the reverse position.

This result has been confirmed by other photographs, which indicate that the direction of the displacement always depends upon the direction of the revolution in the vortex. If this relation is found by future observations to hold generally, we may conclude that the field is always produced by the revolution of particles carrying charges of like sign.

PLANE POLARIZATION ACROSS THE LINES OF FORCE

So far we have confined our attention to polarization phenomena observed along the lines of force. But it is well known that the doublets are, in general, transformed into triplets, when observed in a magnetic field at right angles to the lines of force. The components of the triplets are plane polarized, the central line in a plane at right angles to the plane of polarization of the side components. It should be possible to detect similar phenomena in spot spectra, if they are produced in a magnetic field.

It naturally happens that these spectra are most commonly observed when the spots are not very far removed from the center of the sun, because foreshortening near the limb reduces the umbra to a narrow strip difficult to keep on the slit. This may partially explain why our photographs of spot spectra, taken without polarization apparatus, show the doublets without a trace of a central component. But it does not account for the failure of the central line to appear in the spectra of spots well removed from the center. It is true that a few triplets occur in all of our spot spectra, such as λ 5781.97, λ 6064.85, and λ 6173.55. But these I have regarded as probable examples of an exceptional type of lines, observed in the laboratory as triplets along the lines of force. Mitchell records certain cases in which many spot doublets were seen as triplets,[1] but he also notes the existence of doublets in the spectra of spots near the limb.[2] In

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[1] *Astrophysical Journal*, **24**, 80, 1906.

[2] *Ibid.*, **19**, 357, 1906.

PLATE XXIX

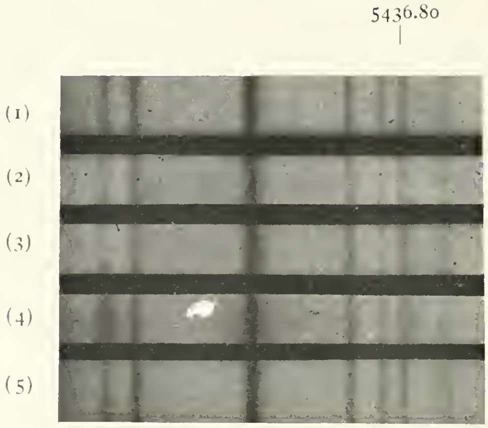

Fig. 1.—(1) and (5) Solar spectrum. (2) Spectrum of a spot near limb, Nicol 60 E. (3) Spectrum of a spot near limb, Nicol 60 W. (4) Spectrum of a spot near center, without rhomb or Nicol. Scale: 1 Ångström=6 mm.

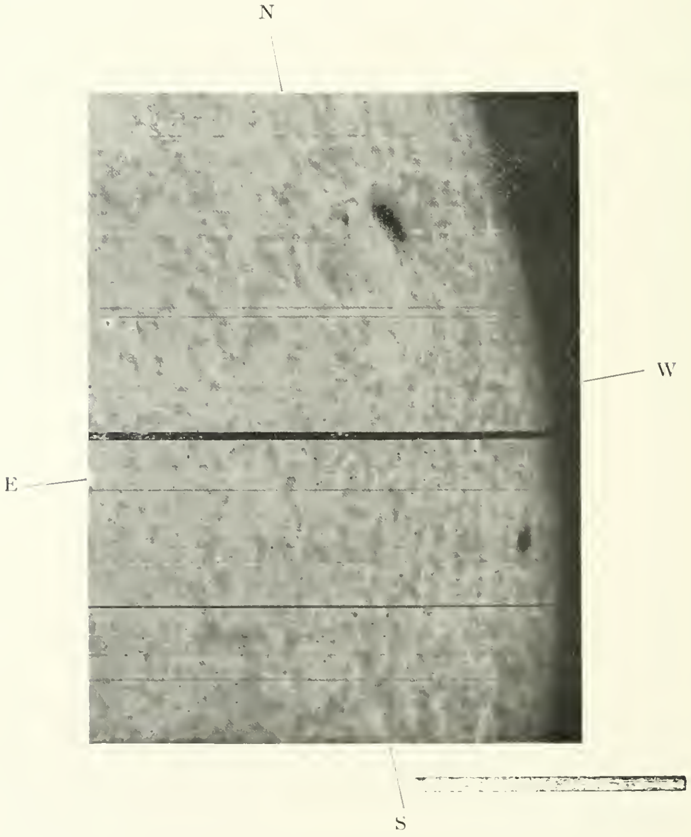

Fig. 2.—Spots near western limb, in which plane polarization of lines was observed.

1908, Sept. 14, 7^{h} 05^{m} A. M. Scale: Sun's Diameter=0.3 Meter.

one interesting observation described and illustrated by Mitchell, the lines appeared double across the umbra and one side of the penumbra, while on the other side of the penumbra they changed into triplets.[1] Since the beginning of my work on the Zeeman effect in the sun, there have been few opportunities to observe the spectra of spots near the limb. These I have utilized, not in attempting to photograph the triplets (which will be tried later), but in testing the polarization phenomena of the spot lines.

The rhomb was removed, and the Nicol employed alone. At right angles to the lines of force the Nicol, when in a certain position, should cut off the outer components of a triplet or the edges of a widened line. In another position, 90° distant, the central component should be extinguished, and the outer components or edges transmitted. Thus, in the second case, lines which are not too diffuse should be photographed as doublets, while in the first case the central component should appear alone.

Plate XXIX reproduces some photographs of a spot near the west limb, made on September 14. The seeing was poor, and neither the *Ha* image nor the spectra are sharply defined. In Fig. 1, Plate XXIX, (1) and (5) represent the solar spectrum; (2) the spot spectrum, photographed with the Nicol set at 60° E.; (3) the spot spectrum, with Nicol set at 60° W.; (4) the same region of another spot spectrum, photographed near center of sun without Nicol. At 60° E. the Nicol cuts out the central line, while at 60° W. it transmits this line and cuts off the side components. Other settings of the Nicol gave the following results, which appear on the same negative (T 200): 90° E., single; 30° E., double; 0°, single, but wide; 30° W., single, but wide. Other photographs, made in this and other regions of the spectrum, gave similar results, the lines being narrow in some positions of the Nicol and wide in others. Only one case of undoubted doubling of the lines has been found. The short time available for work, under favorable atmospheric conditions, when a sufficiently large spot was near the limb, prevented the observations from being carried farther.

LABORATORY TESTS

If the widened lines and doublets in spot spectra are produced by a magnetic field, an equal degree of widening and an equal separation

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[1] *Ibid.*, **24**, 80, 1906.

of the components of doublets should be found in the laboratory when the same lines are observed in a field of equal strength. As the necessary apparatus was fortunately available, the work was at once undertaken in our Pasadena laboratory by Dr. King. A brilliant spark is produced by a high potential transformer between electrodes supported in the field of a large Du Bois magnet. The light, passing through the pierced pole-pieces, falls on a lens, which forms an image of the spark on the slit of a vertical spectrograph, after reflection on a mirror mounted at an angle of 45° above the slit. This spectrograph, which is precisely similar to the 30-foot spectrograph used with the tower telescope, also stands in a constant temperature well, with the slit about three feet above the floor of the laboratory.[1] It may be used as an instrument of 30 feet focal length, or, as in the present case, a 5-inch (13 cm) objective of 13 feet (4 m) focal length, with a 5-inch plane grating, having 14,438 lines to the inch (567 to the mm), can be swung into the axis of collimation 13 feet below the slit. With this shorter focal length the dispersion in the second or third order of the grating is amply sufficient for the present purpose.

If all of the doublets observed in spot spectra could be photographed in the laboratory, it would be easy to make a satisfactory comparison. Unfortunately, however, most of these lines are very faint in the spark, and as the great majority of them occur in the less refrangible part of the spectrum, exposures of from fifteen to twenty hours are sometimes required to bring out even the stronger doublets. The results hitherto obtained for the iron doublets are brought together in the following table. I am indebted to Mr. Adams for

TABLE I

IRON DOUBLETS

Wave-Length	$\Delta\lambda$, Spark	$\frac{\Delta\lambda\text{, Spark}}{5.1}$	$\Delta\lambda$, Spot	δ	$\frac{\Delta\lambda\text{, Spark}}{\Delta\lambda\text{, Spot}}$
6213.14	0.703	0.138	0.136	−0.002	5.2
6301.72	0.737	0.144	0.138	−0.006	5.3
6302.71	1.230	0.241	0.252	+0.011	4.9
6337.05	0.895	0.175	0.172	−0.003	5.2

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[1] Hale, "The Pasadena Laboratory of the Mount Wilson Solar Observatory," *Contributions from the Mount Wilson Solar Observatory*, No. 27; *Astrophysical Journal*, 28, 244, 1908.

these measures and for many of the others given in this paper. Miss Burwell and Miss Wickham have also assisted in the measurement of the spot and spark photographs.

The first column gives the wave-length of the doublet; the second, the separation in Ångströms of the components, observed along the lines of force in a field of about 15,000 gausses;[1] the third, the quantity given in column 2 divided by 5.1; the fourth, the separation of the components observed in the spot spectrum; the fifth, the residuals obtained by substracting the quantities in the third column from those in the fourth; the last column gives the ratio of the separation in the spark, for a field of about 15,000 gausses, to the observed separation in the spot. The mean value of this ratio, 5.1, gives an approximate measure of the strength of the field in spots, which comes out about 2900 gausses.

The agreement between the spot and laboratory results is so close that it can hardly be the result of chance. But when we come to the case of titanium, observed in the laboratory in a field of about 12,500 gausses, we find a very different condition of affairs.

TABLE II

TITANIUM DOUBLETS

Wave-Length	$\Delta\lambda$, Spark	$\frac{\Delta\lambda\text{, Spark}}{5.1}$	$\Delta\lambda$, Spot	δ	$\frac{\Delta\lambda\text{, Spark}}{\Delta\lambda\text{, Spot}}$
5903.56	0.732	0.144	0.086	−0.058	8.5
5938.04	0.737	0.145	0.080	−0.065	9.2
6064.85	0.876	0.172	0.184	+0.012	4.8
6303.98	0.493	0.097	0.093	−0.004	5.3
6312.46	0.615	0.121	0.091	−0.030	6.8

If we use the factor 5.1 employed in the case of iron, we find that two of these doublets, λ 6064.85 and λ 6303.98, agree closely in spot and spark. In some of our spot photographs λ 6064.85 appears to be a triplet, though the components are not clearly separated. With the rhomb and Nicol a faint central component persists when either the red or the violet component is cut off. It is possible that this central line is due to some substance other than titanium in the spot, but it

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[1] This value of the field strength may be in error by 1000 gausses, because of the disturbing effect of the iron electrodes.

is certainly very nearly in the position of the solar titanium line.[1] λ 6312.46 gives a residual of 0.03 Ångströms, which exceeds the error of measurement. The other doublets, λ 5903.56 and λ 5938.04, show in the spot spectrum but little more than one-half the separation that would be expected on the assumption that the strength of the field is the same for all of these lines.

On consideration it will be seen, however, that the separation of the doublets must depend, in some degree, on the distribution of the absorbing vapor in the solar atmosphere, and on the coefficient of absorption of the particular line employed. A striking instance of this kind, affecting lines of the same series, is illustrated in the case of hydrogen, described in a previous paper.[2] Although the $H\delta$ line extends to the upper part of the chromosphere and prominences, the mean level represented by its absorption is much lower than that given by $H\alpha$. The consequence is that $H\alpha$ enables us to photograph the solar vortices, the characteristic stream lines of which do not appear at the lower $H\delta$ level. Similarly, if the intensity of a given titanium line falls off rapidly, the level represented by this line may be comparatively low. If, on the other hand, its intensity curve is of such a form as to indicate that the absorption at higher elevations plays an important part, the mean level represented by the line may be considerably higher than in the previous case. To settle this question we must know: (1) The range of elevation in the spot of the vapors of iron, titanium, and other elements; (2) the intensities of the lines of these elements at different levels; (3) the rate at which the strength of the field decreases upward.

In the absence of information regarding the first two points, we may inquire as to the probable relative behavior of titanium, iron, and other elements if the distribution of the vapors at different levels were the same as in the chromosphere. From a discussion of a large number of photographs of the flash spectrum, made by different observers at several eclipses, Jewell has compiled a table showing the heights above the sun's limb attained by various lines in

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[1] It is conceivable that under conditions analogous to those that give rise to the H_3 and K_3 lines, a doublet might be produced within the strong magnetic field of the spot, and a single line, at the center of the doublet, by the absorption of the vapor at a high level, where the field strength is low.

[2] *Solar Vortices*, p. 3.

the blue and violet.[1] The heights for titanium range from 100 miles (160 km) for λ 4466.0 to 3500 miles (5640 km) for λ 4466.7, while certain strong enhanced lines in the ultra-violet reach elevations of 6000 or 8000 miles (9660 or 12,880 km). For iron the minimum height is 200 miles (320 km) for λ 4482.4 and the maximum 1000 miles (1610 km) for λ 4584.0. Chromium ranges from 100 miles for λ 4280.2 to 1200 miles (1930 km) for λ 4275.0; manganese from "100 miles or more" for λ 4451.8 to "800 miles (1290 km) or more" for λ 4030.9; vanadium from 100 miles for λ 4390.1 to 200 miles for λ 4379.4. It thus appears that the range in level represented by the titanium lines is much greater than for the lines of iron, chromium, manganese, and vanadium. If the vapors were similarly distributed in spots, the maximum strength of field indicated by the titanium lines should therefore correspond with the maximum value for iron, but some titanium lines, produced by absorption at higher mean levels, should give lower field strengths. Chromium should agree more nearly with iron. Vanadium, if the less refrangible lines reach no greater elevations, should give closely accordant (maximum) values for the field strength. It will perhaps be possible, with the aid of the 30-foot spectrograph, to determine the relative levels in the chromosphere attained by most of the lines in question, but it is a much more difficult matter to do this for sun-spots. I hope, however, that our new spectroheliograph of 30-feet focal length may throw some light on this subject.

It is evident that these considerations will have no bearing on the present problem, unless the field strength decreases very rapidly upward in spots. That this probably occurs is shown by the fact that the D lines of sodium and the *b* lines of magnesium are usually but slightly affected in the spot spectrum,[2] and are displaced through a very small distance when the Nicol is rotated. Thus, at the level represented by these lines, which attain elevations in the chromosphere probably not exceeding 5000 miles, the field strength is reduced to a small fraction of its maximum value.

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[1] "Total Solar Eclipses of May 28, 1900, and May 17, 1901," *Publications of the U. S. Naval Observatory*, Second Series, Vol. IV, Appendix I.

[2] Except for the strengthening of the wings, which may be produced by some cause other than a magnetic field.

The following doublets have been measured in the spectrum of chromium:

TABLE III

CHROMIUM DOUBLETS

Wave-Length	$\Delta\lambda$, Spark	$\frac{\Delta\lambda,\text{ Spark}}{4.9}$	$\Delta\lambda$, Spot	δ	$\frac{\Delta\lambda,\text{ Spark}}{\Delta\lambda,\text{ Spot}}$
5304.36	0.636	0.130	0.188	+0.058	3.4
5387.16	0.676	0.138	0.085	−0.043	8.0
5713.00	0.610	0.124	0.161	+0.037	3.7
5781.40	0.755	0.154	0.121	−0.033	6.2
5781.97	0.922	0.188	0.212	+0.024	4.3
5783.29	0.772	0.158	0.137	−0.021	5.6
5784.08	0.720	0.147	0.121	−0.026	6.0
5785.19	0.707	0.144	0.137	−0.007	5.1

In photographing these lines in the spark, the strength of the field was 12,500 gausses. The strength of the field in spots, as indicated by the mean separation of the chromium doublets, is therefore 2600 gausses.

The above tables comprise all of the doublets hitherto observed both in spots and in our laboratory. It was at first hoped that the shifts of lines, on photographs of the spot spectrum made with the rhomb and Nicol, would serve as satisfactory data for comparison with laboratory results. But when the small magnitudes of these shifts, and the wide differences in the character of the lines were taken into account, it appeared that comparisons based on such data could have but little weight.

When a line is clearly resolved into a doublet, rotation of the Nicol cuts off the right-handed or left-handed light, and produces a shift equal to the separation of the components. But when the strength of the field is only sufficient to widen a line, that portion of the widened line where the right-handed and left-handed components overlap is composed of ordinary unpolarized light, not affected by rhomb or Nicol. If the components are narrow, this region may also be narrow. But if they are broad, only the outer edges of the components will be cut off when the Nicol is rotated.

If a magnetic field is the principal cause of the widening of lines in spots, their widths should be roughly proportional to the separation of the components of the corresponding doublets observed in a field of equal strength. Bearing in mind the differences in the character of the lines, and the probable effect of variations in the mean level of absorption, we can hardly expect a very close agreement. But some evidences of relationship should appear, if a magnetic field is present. In the following tables the widths of various iron lines are compared with the separations of their components in the spark. To facilitate the comparison, the distances between the centers of the components, photographed in a field of about 15,000 gausses, are divided by 2.9, which reduces them to approximate equality with the widths in spots.

TABLE IV

WIDTHS OF IRON LINES IN SPOTS

Wave-Length	$\Delta\lambda$, Spark	$\frac{\Delta\lambda\text{, Spark}}{2.9}$	Width in Spots	δ
6136.19	0.38	0.13	0.15	+0.02
6137.92	0.50	0.17	0.16	−0.01
6191.78	0.43	0.15	0.14	−0.01
6219.49	0.59	0.20	0.23	+0.03
6246.54	0.67	0.23	0.24	+0.01
6252.77	0.45	0.16	0.15	−0.01
6265.35	0.55	0.19	0.20	+0.01
6315.52	0.59	0.20	0.16	−0.04 Enhanced line
6318.24	0.40	0.14	0.14	0.00
6335.55	0.55	0.19	0.20	+0.01
6393.82	0.46	0.16	0.18	+0.02
6400.22	0.58	0.20	0.22	+0.02
6411.86	0.56	0.19	0.17	−0.02
6417.13	0.69	0.24	0.15	−0.09 Enhanced line
6420.17	0.57	0.20	0.19	−0.01
6421.57	0.64	0.22	0.18	−0.04
6431.07	0.54	0.19	0.19	0.00
6456.60	0.55	0.19	0.22	+0.03 Enhanced line
6495.21	0.54	0.19	0.18	−0.01

The exceptionally large residuals of the enhanced lines may be due to the fact that the weakening of these lines in spots makes them very difficult to measure. But it is perhaps possible that another cause may account for the negative sign of most of their residuals in Tables IV and VI. Assume that in the lower part of spots the field is most intense and the reduction of temperature most marked. In consequence of the reduced temperature, the enhanced lines are greatly weakened. Hence an unusually large proportion of the absorption which gives rise to these lines may occur at greater elevations, where

TABLE V

Widths of Iron Lines in Spots

Wave-Length	$\Delta\lambda$, Spark	$\frac{\Delta\lambda,\ \text{Spark}}{2.9}$	Width in Spots	δ
5083.58	0.41	0.14	0.15	+0.01
5098.88	0.42	0.14	0.13	−0.01
5107.62	0.25	0.09	0.11	+0.02
5107.82	single*		0.14	
5110.57	0.45	0.15	0.17	+0.02
5123.90	single		0.09	
5125.30	0.41	0.14	0.09	−0.05
5127.53	0.51	0.18	0.15	−0.03
5137.56	0.45	0.15	0.13	−0.02
5139.43	0.56	0.19	0.16	−0.03
5139.64	0.51	0.18	0.15	−0.03
5143.11	0.42	0.14	0.11	−0.03
5162.45	0.47	0.16	0.14	−0.02
5167.68	0.35	0.12	0.12	0.00
5171.78	0.39	0.13	0.15	+0.02
5191.63	0.57	0.20	0.18	−0.02
5192.52	0.56	0.19	0.17	−0.02
5195.11	0.33	0.11	0.14	+0.03
5198.89	single		0.10	
5208.78	0.48	0.16	0.14	−0.02
5215.35	0.45	0.15	0.15	0.00
5216.44	0.23	0.08	0.12	+0.04
5217.55	0.47	0.16	0.15	−0.01
5227.04	0.47	0.16	0.19	+0.03
5227.36	0.32	0.11	0.15	+0.04
5230.03	0.50	0.17	0.15	−0.02
5233.12	0.38	0.13	0.14	+0.01
5242.66	0.29	0.10	0.11	+0.01
5250.82	0.49	0.17	0.14	−0.03
5263.49	0.47	0.16	0.13	−0.03
5266.74	0.38	0.13	0.14	+0.01
5269.72	0.39	0.13	0.15	+0.02
5273.56	0.53	0.18	0.11	−0.07
5276.17	0.31	0.11	0.12	+0.01
5281.97	0.44	0.15	0.11	−0.04
5283.80	0.49	0.17	0.14	−0.03
5302.48	0.48	0.17	0.17	0.00
5316.79	0.32	0.11	0.11	0.00 Enhanced line
5324.37	0.48	0.16	0.16	0.00
5328.24	0.37	0.13	0.17	+0.04
5328.70	0.49	0.17	0.13	−0.04
5340.12	0.48	0.16	0.16	0.00
5365.07	0.30	0.10	0.10	0.00
5367.67	0.31	0.11	0.12	+0.01
5370.17	0.36	0.12	0.12	0.00
5371.73	0.33	0.11	0.16	+0.05
5383.58	0.37	0.13	0.13	0.00
5393.38	0.52	0.18	0.18	0.00
5397.34	0.48	0.16	0.20	+0.04
5400.71	0.42	0.14	0.11	−0.03

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* "Single" in these tables does not mean that the line is not affected by the field, but merely that it was not clearly separated on the plate measured. Several of these photographs were made in the first order.

TABLE V—*Continued*

Wave-Length	$\Delta\lambda$, Spark	$\frac{\Delta\lambda\text{, Spark}}{2.9}$	Width in Spots	δ
5404.36	0.38	0.13	0.16	+0.03
5405.99	0.23	0.08	0.15	+0.07
5411.12	0.40	0.14	0.13	−0.01
5415.42	0.38	0.13	0.15	+0.02
5424.29	0.40	0.14	0.15	+0.01
5429.92	0.48	0.16	0.16	0.00
5434.74	single		0.11	
5447.13	0.51	0.18	0.19	+0.01
5455.83	single		0.20	

the temperature is higher and the field weaker. In this case, the field intensities indicated by the enhanced lines should be below the average value. In view of the fact that the rate of change of intensity with level is not the same for all lines, it is evident that many more cases must be included in any satisfactory test of this hypothesis. From the same course of reasoning it follows that lines which are most strengthened in spots should, in general, be most widened. This appears to be true, but a careful quantitative comparison will be made, both for strengthened and weakened lines, and published in a subsequent paper. It must not be forgotten that a considerable increase of temperature in the higher spot vapors would tend to produce true reversals. Discussion of this question must be reserved, however, until the spot spectra can be more thoroughly studied with this point in view.

In Table IV the mean residual, taken without regard to sign, is 0.021 Ångströms. If we omit the enhanced lines, because of their exceptional behavior in spots, the mean residual is reduced to 0.015 Ångströms. As the spot lines range in width from 0.14 to 0.24 Ångströms, the agreement is closer than would be expected to result from chance alone. When it is remembered that one or more secondary causes may also affect the width of the lines, the probability that a true relationship exists appears to be considerably increased.

A more refrangible region of the iron spectrum gives the results detailed in Table V.

Here the mean residual is 0.021 and the range in the width of the spot lines from 0.09 to 0.20 Ångströms. λ 5107.82, λ 5123.90, λ 5198.89, and λ 5434. 74, which are very narrow in spots, are not quite separated on the laboratory plates. λ 5455.83, on the contrary, is single in the laboratory and fairly wide in spots. In this case, at least, there must be some cause of widening in spots other than a magnetic field.

A still more refrangible region of the iron spectrum gives the results contained in the following table:

TABLE VI

WIDTHS OF IRON LINES IN SPOTS

Wave-Length	$\Delta\lambda$, Spark	$\frac{\Delta\lambda, \text{ Spark}}{2.1}$	Width in Spots	δ
4427.48	0.32	0.15	0.16	+0.01
4433.39	0.28	0.13	0.12	−0.01
4442.51	0.35	0.17	0.18	+0.01
4443.36	0.10	0.05	0.12	+0.07
4454.55	0.26	0.12	0.10	−0.02
4459.30	0.32	0.15	0.12	−0.03
4461.82	0.32	0.15	0.14	−0.01
4466.73	0.26	0.12	0.15	+0.03
4469.54	0.32	0.15	0.12	−0.03
4484.39	0.29	0.14	0.12	−0.02
4494.74	0.25	0.12	0.14	+0.02
4522.80	0.20	0.10	0.08	−0.02 Enhanced line
4525.31	0.32	0.15	0.11	−0.04
4528.80	0.27	0.13	0.13	0.00
4531.33	0.29	0.14	0.12	−0.02
4548.02	0.22	0.10	0.10	0.00
4549.64	0.24	0.11	0.10	−0.01 Enhanced line
4556.06	0.27	0.13	0.12	−0.01 Enhanced line
4603.13	0.37	0.18	0.14	−0.04
	Mean 0.27		Mean 0.12	

It is interesting to note the progressive decrease toward the violet in the mean width of spot lines and the separation of the corresponding doublets in the spark, as shown by the following table. The means represent the three groups of lines given in Tables IV, V, and VI.

TABLE VII

Mean Wave-Length	Spot Lines Mean Width	Spark Doublets Mean Separation
6330	0.18	0.54
5267	0.14	0.42
4495	0.13	0.29

Although the rate of decrease is more rapid for the spark doublets than for the spot lines, it must be remembered that in the former case the mean separation of the components is given, while the mean width of the spot lines represents the separation of the components plus their width. The width of the components cannot be determined, except in the case of doublets, and therefore the rate of decrease falls off toward the violet, as the width of the spot lines approaches that of the solar lines. The extremely small average shift of the lines in the violet when the Nicol is rotated is in harmony with this view.

A group of twelve spot doublets near λ 4395, which belong to several different elements and have not yet been photographed in our laboratory, afford some additional evidence. The mean separations of groups of spot doublets in the red (Tables I, *Fe*, and II, *Ti*), green (Table III, *Cr*), and violet (those just mentioned) are given in the following table:

TABLE VIII

Mean Wave-Length	Spot Doublets	
	Number	Mean Separation
6186	9	0.137
5665	8	0.145
4395	12	0.085

Between λ 6186 and λ 5665 these doublets show no such progressive change as appears in Table VII.

Preston's law, $\frac{\Delta\lambda}{\lambda^2}=\text{const.}$, has been found to hold rigorously only for the lines of certain series. It therefore could not be expected to apply with accuracy here, especially as the lines of different elements are included. Nevertheless it is of interest to determine whether the decrease in the separation of these doublets toward the violet proceeds at a similar rate. If we combine the separations for λ 6186 and λ 5665, we have 0.141 for the mean wave-length λ 5941. Then

$$\frac{0.141}{(5941)^2}=4.0\times 10^{-9}$$

$$\frac{0.085}{(4395)^2}=4.4\times 10^{-9}.$$

The iron doublets, whose mean separations for a field strength of about 15,000 gausses are given in Table VII, yield the following results.

$$\frac{0.44}{(5544)^2}=14.3\times10^{-9}$$

$$\frac{0.29}{(4495)^2}=14.3\times10^{-9}.$$

Thus the iron doublets follow the law very closely, while the approximate agreement with the spot doublets, though perhaps the result of chance, is not without interest.

Table IX gives the widths of various titanium lines in spots, and the separations of the components of the corresponding doublets, observed along the lines of force in a field of 12,500 gausses.

TABLE IX

Widths of Titanium Lines

Wave-Length	$\Delta\lambda$, Spark	$\frac{\Delta\lambda,\ \text{Spark}}{3.4}$	Width in Spots	δ
5823.91	single		0.13	
5866.68	0.48	0.14	0.19	+0.05
5880.49	0.64	0.19	0.19	0.00
5899.52	0.50	0.15	0.18	+0.03
5903.56	0.73	0.21	0.19	−0.02
5918.77	0.73	0.21	0.20	−0.01
5922.33	single		0.12	
5938.04	0.74	0.22	0.17	−0.05
5953.39	0.52	0.15	0.13	−0.02
5966.06	0.47	0.14	0.16	+0.02
5978.77	0.38	0.11	0.14	+0.03
6064.85	0.88	0.26	0.27	+0.01
6085.47	0.81	0.24	0.20	−0.04
6091.40	0.65	0.19	0.15	−0.04
6092.74	0.55	0.16	0.16	0.00
6098.87	0.59	0.17	0.15	−0.02
6121.22	0.56	0.16	0.17	+0.01
6126.44	0.64	0.19	0.17	−0.02
6146.44	single		0.12	
6261.32	0.41	0.12	0.16	+0.04
6317.67	0.42	0.12	0.12	0.00
6336.33	0.56	0.16	0.15	−0.01
6366.56	0.55	0.16	0.18	+0.02

For titanium in this region the mean residual is 0.021 Ångströms for spot lines ranging in width from 0.12 to 0.27 Ångströms.

SIGN OF THE CHARGE THAT PRODUCES THE FIELD IN SUN-SPOTS

If the evidence presented in this paper renders probable the existence of a magnetic field in sun-spots, it is of interest to inquire concerning the sign of the charge which, according to our hypothesis, produces the field. In Lorentz's theory of the Zeeman effect in its simplest form, the motion of a single electron in a molecule of a luminous source is discussed.[1] This electron is supposed to be capable of displacement in all directions from its position of equilibrium, toward which it is drawn by an elastic force, which is proportional to the displacement but independent of its direction. Let e be the charge of the particle, m its mass, fr the elastic force caused by a displacement r, f being a positive constant. The frequency of the vibrations, whether they be linear, elliptical, or circular, will be

$$n_0 = \sqrt{\frac{f}{m}}\,.$$

We may now suppose the light-source to be placed in a homogeneous magnetic field of intensity H. A particle carrying a charge e, and moving with velocity v, will be subjected to a force perpendicular to the field and to the direction of motion of the particle, the magnitude of which may be represented by $ev\mathrm{H}\sin(v,\mathrm{H})$. It is evident that the electron may have three different motions, each with its own frequency. Linear vibrations parallel to the lines of force, having the frequency n_0, will not be affected by the magnetic field. Circular vibrations in a plane perpendicular to the lines of force will be affected differently, depending upon whether they are right-handed or left-handed. If r is the radius of a circular orbit and n the frequency, the velocity of the electron will be $v=nr$ and the centripetal force will have the value mn^2r. We may now consider the effect on the motion of the electron of the elastic force fr and of an electromagnetic force

$$ev\mathrm{H} = enr\mathrm{H}.$$

For a positive charge the latter force is directed toward the center if the motion is clockwise, as seen by an observer toward whom the lines of force are directed. We then have

$$mn^2r = fr + enr\mathrm{H}.$$

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[1] The following outline of the theory is taken from Lorentz's "Theorie des phénomènes magnéto-optiques récemment découverts," *Rapports,* Congrès international de physique, 3, 1, 1900.

This frequency n differs very slightly from the frequency n_0; thus the last term of the equation must be much smaller than the term fr, so that we may write

$$n = n_0 + \frac{eH}{2m}\,. \qquad (1)$$

This expression gives the frequency of the right-handed (clockwise) vibrations. For the left-handed vibrations we have

$$n = n_0 - \frac{eH}{2m}\,. \qquad (2)$$

As seen along the lines of force a single line in the spectrum is thus transformed into a doublet, the components of which are circularly polarized. An observer toward whom the lines of force are directed will find that the light of the component of greater wave-length, whose frequency has been decreased by the field, is circularly polarized in the right-handed or clockwise direction. Hence (2) is greater than (1), and it follows that the charge e of the electron which produces the spectral lines must be negative.

In the case of the solar vortices we have to consider two sets of charged particles, which may be entirely distinct from one another: (1) those whose vibrations give rise to the lines in the spectra of spots, and (2) those that carry the charge which, by the hypothesis, produces the magnetic field. The Zeeman effect supplies the means of determining the direction of the lines of force of the sun-spot fields, and photographs of the vortices, made with the spectroheliograph, indicate the direction of their rotation. Thus we are in a position to determine the sign of the charge carried by the particles which produce the fields. As pointed out independently by König and Cornu, the violet component of a magnetic doublet observed along the lines of force is formed by circular vibrations, having the direction of the current flowing through the coils of the magnet.[1] From observations of circularly polarized light, made in our Mount Wilson laboratory by Dr. St. John and confirmed by myself, it appears that when the Nicol prism of the tower spectrograph stands at 60° E. it transmits the violet component of a doublet produced in a magnetic field directed toward the observer. From Biot and Savart's law the direction of

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[1] See Cotton, *Le phénomène de Zeeman*, chap. vii; König, *Wied. Ann.*, **62**, 240, 1897.

the current causing such a field is counter-clockwise, as seen by the observer. In the same position the Nicol also transmits the violet component of a doublet produced in a sun-spot surrounded by a vortex rotating clockwise. As a negative charge rotating clockwise produces a field of the same polarity as an electric current flowing counter-clockwise, we may conclude that the magnetic field in spots is caused by the motion of negative ions or electrons.

PROBABLE SOURCE OF THE NEGATIVE CORPUSCLES

We may now consider the probable source of a sufficient number of negative corpuscles to produce a field of about 2900 gausses in sun-spots.

In his *Conduction of Electricity through Gases*, p. 164, J. J. Thomson writes as follows:

> We thus are led to the conclusion that from an incandescent metal or glowing piece of carbon "corpuscles" are projected, and though we have as yet no exact measurements for carbon, the rate of emission must, by comparison with the known much smaller rate for platinum, amount in the case of a carbon filament at its highest point of incandescence to a current equal to several amperes per square centimeter of surface. This fact may have an important application to some cosmical phenomena, since, according to the generally received opinion, the photosphere of the sun contains large quantities of glowing carbon; this carbon will emit corpuscles unless the sun by the loss of its corpuscles at an earlier stage has acquired such a large charge of positive electricity that the attraction of this is sufficient to prevent the negatively electrified particles from getting right away from the sun; yet even in this case, if the temperature were from any cause to rise above its average value, corpuscles would stream away from the sun into the surrounding space.

On another page (168) Thomson also remarks: "The emission of the negative corpuscles from heated substances is not, I think, confined to the solid state, but is a property of the atom in whatever state of physical aggregation it may occur, including the gaseous." After illustrating this in the case of sodium vapor, Thomson adds (p. 168):

> The emission of the negatively electrified corpuscles from sodium atoms is conspicuous as it occurs at an exceptionally low temperature; that this emission occurs in other cases although at very much higher temperatures is, I think, shown by the conductivity of very hot gases (or at any rate by that part of it which is not due to ionization occurring at the surface of glowing metals), and especially by the very high velocity possessed by the negative ions in the case

of these gases; the emission of negatively electrified corpuscles from atoms at a very high temperature is thus a property of a very large number of elements, possibly of all.

Thus the chromosphere, as well as the photosphere, may be regarded as copious sources of negatively electrified corpuscles. The part played by these corpuscles in the sun-spots cannot be advantageously discussed until the nature of the vortices is better understood.[1] At present it is enough to recognize that the supply of negative electricity appears amply sufficient to account for the magnetic fields.

Let n be the number of corpuscles per unit cross-section passing a given point in unit time and e the charge on each corpuscle. Then we have, for the current carried by the corpuscles, $c=ne$. H. A. Wilson found that in a vacuum tube, at pressures up to 8.5 mm, the current at the cathode was $0.4\ p$ milliamperes per sq. cm, where p is the pressure in millimeters.[2] If $p=8.5$, we have $c=3.4\times 10^{-3}$ amperes. Assume the velocity of the corpuscles in this case to be of the order of 10^4 km per sec. In a solar vortex (if the charged particles are carried with it) the velocity may be taken as of the order of 100 km per sec.[3] Then if the number of corpuscles per sq. cm were the same in the two cases, the current in the sun would be of the order of 3.4×10^{-5} amperes per sq. cm at the same pressure.

We may now assume the corpuscles to be moving at a velocity of 100 km per second in an annulus 25,000 km wide, 1000 km deep, and 100,000 km in diameter surrounding a sun-spot. Taking the current strength to be as above, 3.4×10^{-5} amperes per sq. cm, the intensity of the resulting magnetic field comes out 1000 gausses.

Such a calculation is of little value, except for the purpose of indicating that a magnetic field of the observed order of magnitude might conceivably be produced on the sun.[4]

EXTERNAL FIELD OF SUN-SPOTS

We have already seen that the strength of the field in spots apparently changes very rapidly along a solar radius, and is small at the upper level of the chromosphere.

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[1] For this reason a discussion of the very interesting suggestion of Professor E. F. Nichols, that the positively and negatively charged particles are separated by centrifugal action in the spot vortex, is reserved for a subsequent paper.

[2] *Philosophical Magazine* (6), 4, 613, 1902.

[3] *Solar Vortices*, p. 13.

[4] See a similar calculation by Zeeman in *Nature* for August 20, 1908.

If subsequent work proves this to be the case, it will appear very improbable (as indicated by theory) that terrestrial magnetic storms are caused by the direct effect of the magnetic fields in sun-spots. Their origin may be sought with more hope of success in the eruptions shown on spectroheliograph plates in the regions surrounding spots.

CONCLUSION

Although the combined evidence presented in this paper seems to indicate the probable existence of a magnetic field in sun-spots, the weak points of the argument should be clearly recognized. Among these are the following:

1. The failure of our photographs to show the central line of spot triplets before the spots are very close to the limb.

2. The presence in the spot spectrum of at least one triplet, which appears as a doublet when observed along the lines of force in the laboratory.

3. The absence of evidence to support the hypothesis that the imperfect agreement between spot and laboratory results is due to differences in the mean level of absorption.

4. The apparent constancy of the field strength, as indicated by the nearly uniform width of the doublets in different spots.

5. The difficulty of explaining, on the basis of our present fragmentary knowledge of solar vortices, the observed strength of field in the umbra and penumbra, and especially its variation with level.

As the resolving power of the 30-foot spectrograph is sufficient to resolve completely only the wider spot doublets, the central line could not be separately distinguished in other cases, even if it were present. Hitherto it has been possible to photograph the spectra of only the largest spots, because the images of other spots, as given by the tower telescope, are too small. The need of a telescope giving a much larger image of the sun, and a spectrograph of greater resolving power and focal length, which has been felt in previous work, is strongly emphasized by this investigation. Such apparatus would also permit the spectrum of the chromosphere, and many other solar phenomena, to be studied to great advantage.

As regards the nature of the vortices, the principal question is whether the gyratory motion primarily concerned in the production of the magnetic field is outside the boundaries of the spot or within the umbra. In the former case we must face various difficulties, such as the apparent constancy of the field in different spots, and the fact that its intensity rapidly decreases upward. If a spot vortex may be considered analogous to an anti-cyclone, and the assumption be made that the gyratory motion of the low-level vapors produces the field, these difficulties may be lessened. The view that the field is produced by the gyratory motion of vapors within the umbra raises other difficulties which may also be serious. Fortunately there is reason to hope that observations now in progress may throw light on several of these questions.

Mount Wilson Solar Observatory
October 7, 1908

ADDENDUM

The fact that the doublets in the sun-spot spectrum do not change to triplets, even when the spot is as much as 60° from the center of the sun, appeared, when the proof of the above paper was corrected, to be a serious argument against the magnetic field hypothesis. Thanks to the recent work of Dr. King, this difficulty no longer exists, at least in the case of several iron and titanium lines. Photographs of the spark spectrum in a strong magnetic field, taken at right angles to the lines of force, show that the iron lines $\lambda\lambda$ 6213.14, 6301.72, and 6337.05 are doublets, with no trace of a central component. As these lines are also doublets when observed parallel to the lines of force, it is only natural that they should be double in spots, wherever situated on the solar disk. λ 6173.55, which is a fine triplet in spots, is a triplet when observed at right angles to the lines of force. But the line λ 6302.71 is the most interesting of all. In Table I this is classed as a spot doublet. In the spot spectrum the line appears as a triplet, but so decidedly asymmetrical that I supposed the intermediate line to be due to some element other than iron, greatly strengthened in the spot. It now turns out, however, that this is an asymmetrical triplet in the spark, when observed at right angles to the lines of force. Moreover, the displacement of the intermediate line from the center is toward the red, both in the spot and in the spark. As soon as a suitable photograph can be taken in a higher order of the grating, it will be possible to measure the asymmetry in the spark, as has already been done in the spot spectrum.

The titanium lines λλ 6303.98 and 6312.46, which are double in spots, are also double in the spark, when observed at right angles to the lines of force. λ 6064.85, already mentioned as a triplet in spots, with a rather faint central component, is a triplet, with strong central component, in the spark under the above conditions.

The titanium spot doublets λλ 5903.56 and 5938.04 (Table II) have not yet been observed at right angles to the lines of force.

These results leave no doubt in my mind that the doublets and triplets in the sun-spot spectrum are actually due to a magnetic field. As I am now designing a spectrograph of 75 feet (23 m) focal length, for use with a tower telescope of 150 feet (46 m) focal length, I hope it may become possible to investigate small spots, as well as large ones, and to resolve many of the close doublets and triplets in their spectra.

November 4, 1908

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The scope of the ASTROPHYSICAL JOURNAL includes all investigations of radiant energy, whether conducted in the observatory or in the laboratory. The subjects to which special attention is given are photographic and visual observations of the heavenly bodies (other than those pertaining to "astronomy of position"); spectroscopic, photometric, bolometric, and radiometric work of all kinds; descriptions of instruments and apparatus used in such investigations; and theoretical papers bearing on any of these subjects.

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A NEW METHOD FOR MEASURING THE INDEX OF REFRACTION OF A GAS FOR DIFFERENT LIGHT-WAVES AND RESULTS OBTAINED FOR SEVERAL GASES

By HARVEY CLAYTON RENTSCHLER

INTRODUCTION

1. *Previous determinations of refractive indices of gases.*—The problem of finding the index of refraction of a gas, and its relation to the density of the gas, is an old one and one which has been undertaken by a great many investigators. The earliest value for the index of refraction of air was deduced from astronomical observations, for white light, by Delambre.[1] Biot and Arago[2] used a hollow prism filled with air and observed, by means of a telescope, the apparent change of position of an object seen through the prism, when the pressure of the air in the prism was changed.

Ketteler[3] was the first to study the dispersion of gases. Between the plates of a Jamin interferometer he placed two tubes of equal lengths filled with the gas to be investigated. The pressure of the gas in one tube was changed and the fringe shift observed for a known change of pressure. In this way he determined the absolute value for the indices of refraction of yellow sodium light for air, carbon dioxide, hydrogen, sulphur dioxide, and cyanogen. By using a mixture of sodium and lithium in the flame, he observed the number of

[1] Laplace, *Mécanique céleste*, 4, 237, 246, 272, 1805.

[2] *Mém. de l'Inst.*, 7, 301–385, 1806.

Pogg. Ann., **124**, 390, 1865.

red lithium fringes that passed the cross-hair of his telescope at the same time that a definite number of yellow sodium fringes passed, and so determined the relative value of the index of refraction for red lithium light and similarly for green thallium light.

Lorenz[1] repeated some of Ketteler's measurements with sodium and lithium light and determined the refractive indices for air, hydrogen, oxygen, and nitrogen. Mascart[2] measured the absolute values of the indices of refraction of air and chlorine for sodium light and the relative values for the four cadmium lines $\lambda = 6439$, 5378, 5086, and 4800. He divided a beam of light into two parts, which were passed through two parallel tubes filled with the gas, then recombined them and passed them through a spectroscope. If the pressure in the one tube be raised or that in the other lowered, Talbot bands appear in the spectrum, owing to the change in the optical path. By counting the number of bands that pass for a definite change in pressure he determined the index of refraction.

Chappuis and Rivière[3] used a Jamin interferometer to determine the index of refraction of air for sodium light. Walker,[4] using the same method, also determined the indices of refraction of air, hydrogen, carbon dioxide, and ammonia.

Kayser and Runge[5] placed a hollow prism between a large concave grating and the photographic plate and measured the displacements of various spectral lines when the pressure of the air in the prism was changed from zero to ten atmospheres. In this way they determined the indices of refraction of air for different wave-lengths from $\lambda = 5630$ to 2360.

Hasselberg[6] proposed to measure the displacements of the spectral lines when the pressure of the gas in the prism was changed from zero to one atmosphere and then turn the prism through 180° and again measure the displacements.

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[1] *Wied. Ann.*, **11**, 70, 1880.

[2] *Comptes Rendus*, **86**, 321, 1878.

[3] *Ann. de Chim. et de Phys.* (6), **15**, 1888.

[4] *Phil. Trans.*, **201**, 435, 1903.

[5] *Annalen der Physik*, **50**, 293, 1893.

[6] *Ofversigt af Kongliga Veten-skaps. Akademiens Forhandlingar*, November 1892, p. 441.

And recently the refractive index of light in helium and argon has been determined by W. Burton[1] and for helium, gaseous mercury, sulphur, and phosphorus, within the limits of the visible spectrum, by C. Cuthbertson[1] and E. P. Metcalfe.

2. *Relation between density of a gas and the index of refraction.*—Ketteler[2] found that for equal changes of the pressure of a gas there was the same fringe shift and so concluded that $\frac{n-1}{d}=$constant, where n is the index of refraction and d the density.

Mascart[3] concluded, from an extensive research on the effect of pressure on the index of refraction of air, that up to 8 atmospheres pressure $\frac{n-1}{d}=$constant to within limits of experimental error.

Chappuis and Rivière[4] found that, up to 20 atmospheres pressure, for air and carbon dioxide $n-1$ is strictly proportional to the density; while Gale,[5] using a slightly modified form of a Jamin interferometer and an improved device for measuring pressures, found that up to 20 atmospheres, if there is any departure from the law of Gladstone and Dale (namely, $\frac{n-1}{d}=$constant), this departure does not exceed one-tenth of 1 per cent. for air.

3. *Effect of temperature upon index of refraction.*—On varying the temperature of air, Mascart found that the index of refraction decreases more rapidly than the density with increasing temperature, but von Lang[6] obtained an opposite result.

Benoit[7] using a Fizeau expansion apparatus, by observing the shifts of Newton's rings for the same change of pressure of the gas between the plate and lens, when the gas was first at one temperature and then at another, found that for air the diminution of refraction was exactly proportional to the diminution of density, when the temperature was raised. Chappuis and Rivière (*loc. cit.*) obtained the same result for cyanogen and Walker[8] found the same for air, hydrogen, carbon dioxide, and ammonia.

[1] *Nature*, **78**, 45, 1908.

[2] *Pogg. Ann.*, **124**, 390, 1865.

[3] *Comptes Rendus*, **86**, 321, 1878.

[4] *Ann. de Chim. et de Phys.* (6), **15**, 1888.

[5] *Phys. Rev.*, **14**, 1, 1902.

[6] *Pogg. Ann.*, **153**, 448, 1874.

[7] *Journal de Physique*, **8**, 451, 1889.

[8] *Loc. cit.* (*Phil. Trans.*, **201**, 435, 1903.)

4. *Summary.*—From the above data the three following facts are brought out: (1) That air is the only gas for which the index of refraction has been determined experimentally for light of wave-length below $\lambda = 4800$; (2) That $(n-1)$ for a gas is directly proportional to the density of the gas; (3) That the change of refractive index of a gas is exactly proportional to the change of density, when the temperature of the gas is changed.

IMPORTANCE AND OBJECT OF THE PRESENT INVESTIGATION

The indices of refraction of many transparent solids and liquids have been measured over a wide range of wave-lengths not only in the visible but also in the infra-red and ultra-violet parts of the spectrum, and the various dispersion formulae tested. In order to test these same formulae for gases, it is necessary to know the values of the indices of refraction over a much larger range of wave-lengths than have been measured previously. The importance of these measurements, especially for the extreme ultra-violet, where many of the gases absorb light very strongly, was suggested to the writer by Professor R. W. Wood. Again Drude[1] has deduced, from purely optical properties of bodies, a value for $\frac{e}{m}$ which demands a very accurate knowledge of the dispersion.

In comparing different modes of solving the problem the following scheme occurred to me, by which the indices of refraction for different wave-lengths over the entire spectrum could be measured at the same time. The object of the present investigation was to develop this method, and to measure the indices of refraction of several gases as far out in the ultra-violet as possible with the apparatus available.

METHOD

If light consisting of different frequencies of vibration, from a slit wide open, is made parallel and then passed through a Fabry and Perot interferometer to a concave grating, the spectral images of the slit and the Fabry and Perot interference circles are brought to the same focus. In other words, the interference circles due to the different frequencies of vibration of the light are entirely separated, provided the spectral lines are not too close together. If, now, the slit is made

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[1] *Annalen der Physik* (4), 14, 677, 1904.

narrow and the interferometer so placed that the light passes through it normal to the plates, there will appear only sections through the center of the circles, of the same width as the slit-image. Owing to the multiple reflections between the plates these circles are very sharp, their diameters can be measured very accurately, and the order of interference at the center of the circles can be calculated to the hundredth, or, at most, the fiftieth part of a fringe. This consists, in general, of a whole number P and a fraction a. If the interferometer is put in a closed tube with windows at the ends and the gas slowly pumped out, the optical distance between the plates becomes smaller and the interference circles collapse toward the center, new ones appearing on the outside. In order to get the index of refraction of the gas, the number of circles that disappear at the center for a definite pressure change must be known. This number is obtained in the following manner. The fringes are photographed with the gas between the plates at atmospheric pressure. The pressure is then reduced to about one-seventh of an atmosphere and the fringes again photographed. Finally the tube is exhausted and the fringes photographed. The diameters of the circles are then measured and the values of a are calculated for every line in each case. Let the difference between a for atmospheric pressure and a for zero pressure be called a'. Therefore the gas between the plates under atmospheric pressure increases the optical path-difference between any two successive reflections from the same initial ray, emerging from the interferometer, over the path-difference between the same two reflections at zero pressure by some whole number $x'+a'$ wave-lengths. Similarly let a'' represent the difference between a for one-seventh of an atmosphere pressure and a for vacuum and x'' the whole number corresponding to this change of pressure. Accordingly one-seventh of an atmosphere change of pressure produces an increase in path-difference of $x''+a''$, while a change of pressure of one atmosphere produces an increase in path-difference of $x'+a'$ wave-lengths.

But it was shown in the introduction that $n-1$ is directly proportional to the density, or for small pressures where Boyle's law applies, directly proportional to the pressure, so that $x''+a''=\frac{1}{7}(x'+a')$. But x' and x'' are both unknown, so that x' is roughly determined for some line in the visible spectrum by counting the number of circles that form at the center and spread out, while the gas is slowly entering the tube. By trying different numbers for x' in equation $x''+a''=\frac{1}{7}(x'+a')$, that number which gives the value of a'' found by experiment is determined.

Owing to the small dispersion of gases, the value of x' for a second spectral line separated from the first by not more than a few hundred Ångström units is approximately the same as for the first line except in the immediate neighborhood of an absorption band. (Here the lines must be closer together or extra readings at pressures between zero and atmospheric pressure must be taken in order to determine x' definitely. It is very desirable in the neighborhood of an absorption band to have the lines close together for another reason, namely, to get more points on the dispersion-curve where it changes most rapidly. The exact value of x' for this second line is found in the same way as for the first line and so on throughout the entire spectrum.

The following values observed for air will serve to make the above clear. For the line 5769 at 0.25 cm of mercury pressure a was 0.497; at 12.26 cm pressure a was 0.819, and at 74.95 cm pressure a was 0.815. That is, a change of pressure of 74.70 cm (0.25 cm to 74.95 cm) produced a change in the optical path of $(x'+0.318)$ wave-lengths; while a change of pressure (from 0.25 cm to 12.26 cm) of 12.01 cm produced a change of $(x''+0.322)$ wave-lengths. But the second pressure-change is $\frac{1}{6.22}$ that of the first and therefore $(x''+0.322)=\frac{1}{6.22}(x'+0.318)$. It was found by visual observation that x' for the line 5460 was 8 and so x' in the above equation cannot differ from 8 by more than two or three units. The following table gives the calculated values for a'' corresponding to all values of x' from 2 to 14. The value of a'' observed was 0.322. It is at once evident that the only value of x' in the neighborhood of 8, for which th observed and calculated values of a'' agree, is 8. While for $x''=14$ the observed and calculated values of a'' agree fairly well, this value is out of the question, as it would indicate the doubling of the index of refraction, from $\lambda=5460$ to λ 5769, in a region with no absorption band.

Again, for an extra reading at say $\frac{1}{13}$ of an atmosphere pressure, the observed and calculated value taking $x'=14$ would have disagreed. Such an extra reading was taken for every other gas than air. This was deemed unnecessary for air, as all the preliminary work was done with air and so the approximate values were known to within one or two units.

$x'+0.318$	$x''+a''$ calculated from first column, using equation $(x''+a'')=\frac{1}{6.22}(x'+a')$
2.318	0.37
3.318	0.53
4.318	0.69
5.318	0.85
6.318	1.01
7.318	1.17
8.318	1.33
9.318	1.49
10.318	1.66
11.318	1.82
12.318	1.98
13.318	2.14
14.318	2.30

APPARATUS

The apparatus used is outlined in Fig. 1. A fused quartz vacuum mercury arc lamp *a* (which will be described more in detail below) was placed in front of the slit *b*. The light from the slit was made parallel by the concave glass mirror *c* of about eight inches focal length. The concave side was nickel-plated by the cathode discharge in a vacuum, nickel being used because of its reflecting power in the ultra-violet. *m* is a brass tube six inches long and three inches in diameter. To one end of this tube is soldered the brass plate *n*. In the middle of this plate there is a hole one inch square, covered by a quartz window *d*, attached to the plate with sealing-wax. To the other end of the tube is soldered a brass collar *g*. *h* is a brass plate with a hole one inch square in the center, covered by a quartz window *d'*. This plate *h* is joined to the collar *g* by means of six screws so that the tube can be opened and closed easily. A washer of pure gum is put between *g* and *h* to make the joint air-tight. The side tube *o* leads to a closed mercury manometer on which the pressure readings are taken with a cathetometer. The vessel *m* is connected to a Geissler-Toepler air pump through the side tube *s*, while *t* leads to the drying tube (a tube about eight inches long filled whith phosphorus pentoxide) and thence to the gas tank. The stopcocks *x* and *y* serve to disconnect the apparatus from the pump and gas-tank respectively. The grating *k* had a focal length of 29.15 cm, and a ruled space of 2.5 inches with 14,000 lines to the inch. Unfortunately the grating is badly scratched, so that all but a small part of it had to be covered with black paper. Furthermore it gives the ultra-violet lines so weakly that, with the light passing first through the interferometer and then to the grating, no trace of any lines below $\lambda = 2967$ could be obtained even after an exposure of one and a half hours. The plate-holder is represented in the figure at *l*. Seed's "Orthochromatic" films were the only kind found to give satisfactory results for the green and yellow mercury lines and were used exclusively.

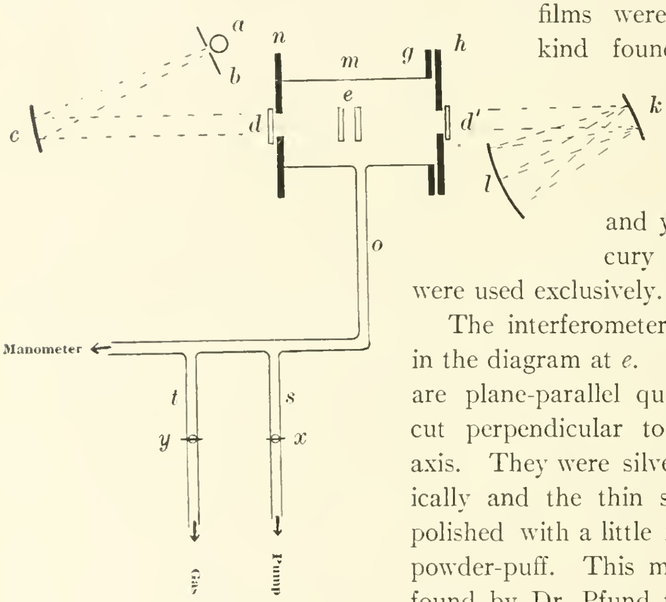

Fig. 1

The interferometer is shown in the diagram at *e*. The plates are plane-parallel quartz plates cut perpendicular to the optic axis. They were silvered chemically and the thin silver films polished with a little rouge on a powder-puff. This method was found by Dr. Pfund to work so remarkably well that the number of back-and-forth reflections between the plates is more than doubled.

The interferometer plates were made parallel by pressing them, by means of three springs, against the ends of a fused quartz ring, the ends of which were made very accurately parallel by A. Hilger of London, England. The pressure of any of these springs could be increased or diminished by means of a screw pressing the spring, and so the final adjustments for parallelism could easily be made by simply altering the pressure of one or another of the springs.

The object of using a fused quartz ring was to eliminate as much as possible any slight temperature variations, fused quartz having an extremely low coefficient of expansion.

The support for the plates, etc., was so designed that it fitted neatly into the tube *m* so that it could be slid in and out easily without jarring it when it had to be taken out to make adjustments for parallelism of the plates. With the quartz ring between the plates they were found to keep their adjustment so well that often it was unnecessary to make any readjustments for several days.

The tube *m* was mounted so that it could be rotated slightly about both a vertical and a horizontal axis perpendicular to its length. This was necessary in order to orient the interferometer in such a way that the light went through it normal to the plates, so that the spectral images were sections through the center of the ring systems.

SOURCE OF LIGHT

The selection of a suitable source of light was by no means the easiest part of the investigation. The metallic arcs, like iron, which give very homogeneous radiations, were at once out of the question with the small dispersion of the grating used. Again, the metallic sparks, such as zinc and cadmium, which give lines nicely separated, are not homogeneous enough for interferometer work. A small mercury vacuum arc lamp similar to the Cooper-Hewitt lamp was used in all the preliminary work and found so satisfactory that the following form of quartz lamp was designed and used exclusively for the rest of the time (Fig. 2).

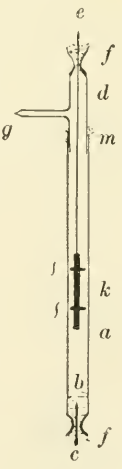

FIG. 2

A fused quartz tube *a* one foot long and $\frac{1}{4}$ inch in diameter had one end drawn out and an iron wire *c* sealed in with sealing-wax *f*. A glass tube *d*, fitting the quartz tube at *m*, was joined to the other end with sealing-wax. A small side tube *g* is used to exhaust it. The top of *d* is drawn out as indicated and an iron wire *e* is sealed in with sealing-wax. This wire is joined to an iron rod *k* about two inches long and about $\frac{3}{16}$ inch in diameter. Two small iron washers keep the rod from hanging to one side. There is about an inch and a half of mercury *b* in the bottom of the tube. The distance between the iron rod and the mercury is about an inch. The lamp is exhausted with a mercury pump. The bottom of the lamp was always kept in water when used, but the top joints remained cool even when used a whole day long. It was joined in series with about 85 ohms to the terminals of the 110-volt D. C. circuit, the iron rod being made the anode. It was started by applying a small flame to the quartz tube and boiling the mercury till it formed contact with the iron rod and lit up. The lamp could be used a whole day long without requiring any attention whatever.

PREPARATION OF THE GASES

The gases used in the present investigation were air, oxygen, nitrogen, carbon monoxide, and carbon dioxide. The gases were collected in a large bottle by displacement of water. The gas was carefully dried by slowly passing it through a tube containing phosphorus pentoxide, as it passed to the vessel where it was used.

The oxygen was prepared by electrolysis of distilled water containing a few drops of pure sulphuric acid.

The nitrogen was prepared by gently heating a solution of ammonium chloride and sodium nitrite.

The carbon monoxide was prepared by heating oxalic acid and concentrated sulphuric acid. The gas thus obtained was slowly bubbled through three different concentrated solutions of potassium hydroxide in order to get rid of all the carbon dioxide formed with the monoxide. The carbon dioxide was prepared with a Gibbs apparatus, from marble and hydrochloric acid. The gas was passed through water to get rid of all traces of acid which might come over with the carbon dioxide.

OBSERVATIONS

Owing to the varying sensitiveness of the photographic film for different wave-lengths and the difference in the intensities of the lines, the time of exposure necessary to give the best results varied for the different lines. An exposure of one minute was sufficient for the three lines λ 4358, 4046, and 3650; while the green line λ 5460 required four minutes and the yellow lines and the ultra-violet line $\lambda = 3341$, twenty minutes. A small cardboard screen was therefore placed in front of the photographic film so that only the yellow and the ultra-violet part of the spectrum from about 3500 down was exposed. After a sufficient exposure had been given to these lines the screen was removed and after one minute more a screen of potassium bichromate was placed in front of the slit. (This transmits only the green and yellow lines and so the green line was given its required length of exposure.)

In all the exposures with the different gases the slit was made just narrow enough to separate the two yellow mercury lines.

The approximate thickness of the ring between the plates being known, the orders of the first interference rings from the center were calculated from an exposure taken with air at atmospheric pressure for the green, the blue, and one of the yellow lines, and so the exact distance between the plates was found to be 9.0065 mm.

For each gas investigated, except air, for which an extra reading was taken, the following six exposures were made, viz.:

1. Vessel containing the interferometer exhausted.
2. Gas in vessel at a pressure of about $\frac{1}{13}$ atmosphere.
3. Gas in vessel under a pressure of about $\frac{1}{6}$ atmosphere.
4. Gas in vessel at atmospheric pressure.
5. Vessel exhausted.
6. Vessel refilled with gas.

The fringe shifts for the various lines due to the difference between the pressures of the gas for the first and fourth exposures were now determined as described in the first part of the paper (exposures two and three serving to get the whole number). Similarly for the difference in pressures for the fourth and fifth exposures and also for the fifth and sixth. From these the fringe shifts for one atmosphere change of pressure were calculated and the mean of the three values determined. But it was shown in the introduction that the index of refraction varies with temperature at exactly the same rate as the density varies with temperature. So that we have at once the fringe shift at 0° C. for a change of pressure of one atmosphere is $(1+at)$ times the mean value determined above (where t is the Centigrade temperature of the gas when the readings were taken, and a is the coefficient of expansion of the gas). From the values thus obtained for the fringe shift at 0° C. for a change of pressure of one atmosphere for the distance between the plates given above, the indices of refraction were calculated for the various lines.

The following figures (Table I) are the values obtained for air and will serve to show how the results agree.

The order in which the exposures were taken is given in column one. Columns two to six give the values of a, calculated from the diameters of the circles for the different mercury lines whose wave-lengths are given above the columns. In the last column are given the pressures of the gas at which the exposures were made. The seventh horizontal row gives the number of fringe shifts for the various pressure changes given at the end of this row. These fringe shifts for the various pressures were obtained from the table in the manner explained in the first part of the paper. In the eighth row are given the fringe shifts calculated for a change of pressure of one atmosphere.

The ninth row shows the average values of row eight, while the tenth row shows the values calculated for 0° C., and the last row gives the refractive indices calculated from the tenth row.

TABLE I

AIR. TEMPERATURE 21°.1 C.

	$\lambda \doteq 5769.6$	$\lambda = 5460.7$	$\lambda = 4358.3$	$\lambda = 4046$	$\lambda = 3650$	$\lambda = 3341$	Pressure
1.............	.815	.622	.217	.324	.435	.837	74.95 cm *Hg*
2.............	.819	.198	.824	.162	.068	.270	12.26
3.............	.497	.812	.067	.250	.928	.930	12.25
4.............	.791	.596	.173	.279	.368	.830	74.67
5.............	.498	.824	.094	.288	.955	.962	74.37
6.............	.807	.605	.202	.314	.381	.841	74.70
From 1 and 3..	8.318	8.810	11.150	12.074	13.507	14.907	74.70
3 and 4..	8.294	8.784	11.106	12.029	13.440	14.900	74.42
4 and 5..	8.293	8.772	11.079	11.991	13.413	14.868	74.30
5 and 6..	8.309	8.781	11.108	12.026	13.426	14.879	74.33
For 76 cm. *Hg* pressure at 21°.1 C.	8.463	8.963	11.344	12.284	13.742	15.166	
	8.470	8.970	11.341	12.284	13.725	15.215	
	8.483	8.973	11.333	12.266	13.720	15.208	
	8.496	8.979	11.358	12.297	13.728	15.213	
Average.....	8.478	8.971	11.344	12.283	13.729	15.200	
For 0° C.......	9.132	9.663	12.219	13.231	14.789	16.373	
Index of refraction......	1.0002925	1.0002930	1.0002956	1.0002972	1.0002997	1.0003036	

The values for the fringe shifts given in row 8, Table I, seldom differ from the average value by more than 0.015 so that the probable error in row 9 should not exceed this amount. This corresponds to an error of not more than four units in the seventh decimal place for the indices of refraction.

RESULTS

In Table II are given the indices of refraction of the different gases investigated for 0° C. and 76 cm *Hg* pressure. The curves of Fig. 3 are plotted with wave-lengths as abscissae and indices of refraction as ordinates.

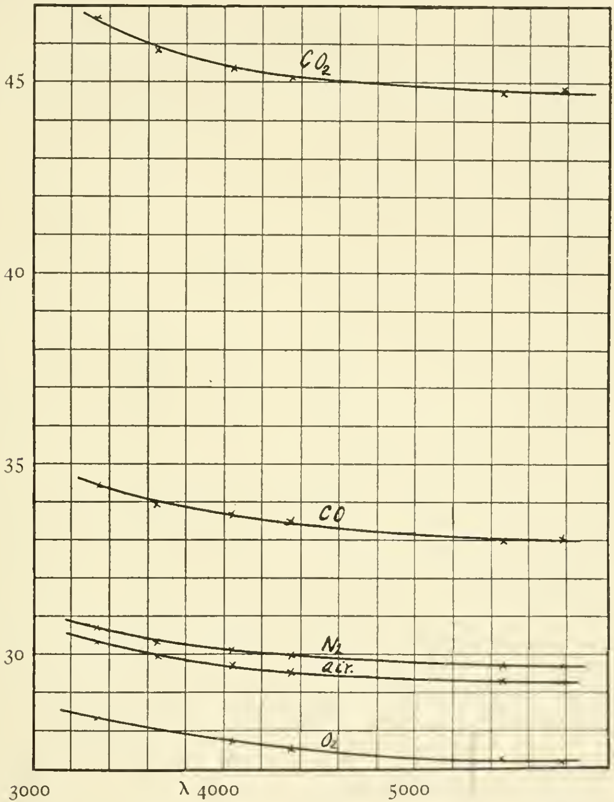

FIG. 3

TABLE II

Gas	λ=5769	5460	4358	4046	3650	3341
Air..........	1.0002925	1.0002930	1.0002956	1.0002972	1.0002997	1.0003036
Oxygen......	1.0002719	1.0002725	1.0002752	1.0002776		1.0002832
Nitrogen.....	1.0002966	1.0002967	1.0002995	1.0003010	1.0003034	1.0003070
CO.........	1.0003303	1.0003299	1.0003346	1.0003366	1.0003396	1.0003442
CO_2.........	1.0004487	1.0004470	1.0004513	1.0004539	1.0004582	1.0004668

The dispersion formulae for the different gases were next calculated. The average value of the indices for the first two lines was taken as the true value for the index for the wave-length which is the mean of the two wave-lengths, and similarly for the next two lines and

TABLE III

AIR. FORMULA $(n-1)\ 10^7=2903.1+3.80\ \lambda^{-2}+1.23\ \lambda^{-4}$

Wave-Length	$(n-1)\ 10^7$ Observed	$(n-1)\ 10^7$ Calculated
5769	2925	2925.6
5460	2930	2929.6
4358	2956	2957.2
4046	2972	2972.2
3650	2997	3000.8
3341	3036	3035.8
NITROGEN $(n-1)\ 10^7=2941+3.81\ \lambda^{-2}+1.21\ \lambda^{-4}$		
5769	2966	2963.4
5460	2967	2967.3
4358	2995	2994.6
4046	3010	3009.4
3650	3034	3037.7
3341	3070	3072.2
OXYGEN $(n-1)\ 10^7=2697.4+3.72\ \lambda^{-2}+1.26\ \lambda^{-4}$		
5769	2719	2719.9
5460	2725	2724
4358	2752	2751.9
4046	2776	2777.1
3650		2795.5
3341	2832	2831.8
CARBON MONOXIDE $(n-1)\ 10^7=3241.2+17.01\ \lambda^{-2}+.58\ \lambda^{-4}$		
5769	3303	3298
5460	3299	3304
4358	3346	3346.7
4046	3366	3366.7
3650	3396	3401.6
3341	3442	3440.1
CARBON DIOXIDE $(n-1)\ 10^7=4490.4-16.55\ \lambda^{-2}+4.03\ \lambda^{-4}$		
5769	4487	4477
5460	4470	4480.3
4358	4513	4515.1
4046	4539	4539.6
3650	4582	4593.1
3341	4668	4665.5

the last two lines. These values were substituted in the three-constant Cauchy formula $n=A+\frac{B}{\lambda^2}+\frac{C}{\lambda^4}$ and the constants found. In Table III are given the formulae thus obtained; the calculated and observed values are tabulated side by side. In these formulae λ is expressed in thousanths of a mm.

For the sake of comparison the indices of refraction of the gases studied in the present work were calculated for yellow sodium light $\lambda=5893$. In Table IV are given the values for the indices of refraction of these gases for sodium light as found by different investigators.

Investigators	Air	Nitrogen	Oxygen	Carbon Dioxide
Ketteler	1.0002947	....	....	1.000449
Lorenz	1.00029108	1.0002960	1.00027155	1.000449
Mascart	1.0002927	....	....	1.000454
Chappuis et Rivière	1.0002919	....	....	....
Benoit	1.0002923	....	....	....
Walker	1.00029288	....	....	1.0004510
Kayser and Runge	1.0002922	....	....	....
Rentschler	1.0002924	1.00029619	1.0002718	1.0004475

CONCLUSIONS

With the method fully developed there will be no difficulty in extending the readings for the refractive indices of the different gases to the extreme end of the ultra violet, provided a good grating is used. As the reflecting power of silver is low in the region from about $\lambda=2800$ to 3150 it would be better to use nickel films on the interferometer plates deposited by the cathode discharge in a vacuum. These nickel films have been used by Fabry and Perot in their work on standard wave-lengths and found very satisfactory. Owing to lack of time I have not yet been able to extend my readings below $\lambda=3341$.

Physical Laboratory
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ANOMALOUS REFRACTION PHENOMENA INVESTIGATED WITH THE SPECTROHELIOGRAPH[1]

By W. H. JULIUS

According to the current interpretation of spectroheliograph results, *dark* flocculi indicate regions on the sun where the special gas, a line of which is used, exists in such conditions of density and temperature, that it strongly absorbs the light coming from deeper layers; whereas *bright* flocculi show us regions where, in consequence of higher temperature or chemical or electrical causes, the radiation of the gas exceeds its absorbing effect.

In a paper,[2] read before the Royal Academy of Amsterdam, in September 1904, I proposed an entirely different explanation of the same phenomena. A first attempt has there been made to account for the peculiar distribution of the light in photographs, secured with the spectroheliograph, by simply considering the anomalous refraction which waves from the vicinity of the absorption lines must suffer when passing through an absorbing medium, the density of which is not perfectly uniform.

If it proves possible to explain the observed facts on this basis, we shall be able to dispense with the assumption of any very marked differences as to the absorbing and emitting conditions of a certain gas or vapor in contiguous regions on the sun. Moreover, we then *might* assume the constituents of the solar atmosphere to be thoroughly mixed, their proportions in the mixture only varying with the distance from the sun's center.

That our interpretation does not presuppose the separate existence of cloudlike masses of calcium or iron vapor or of hydrogen, looks like a simplification and, therefore, an advantage; but even if one were compelled, by other considerations, still to believe in the real existence of such separate luminous or dark accumulations of certain substances, it would nevertheless be necessary to consider the effect

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 29.

[2] *Astrophysical Journal*, **21**, 278, 1905.

which anomalous dispersion in those masses must have on the appearances revealed by the spectroheliograph.

Among the advantages I derived from a visit to the Mount Wilson Solar Observatory in August 1907 was the opportunity of using the 5-foot spectroheliograph for some experiments on anomalous refraction.

It was expected that when light, coming from a source with a continuous spectrum, traverses a space in which sodium vapor is unequally distributed, particulars about the distribution would be revealed by the spectroheliograph through the *refracting* properties of the vapor, rather than through its absorbing and emitting power. This expectation could be put to the test.

As an equipment for the study of anomalous dispersion phenomena in sodium vapor, exactly similar to the one described in my paper on "Arbitrary Distribution of Light in Dispersion Bands,"[1] had already been secured for the Solar Observatory by Director Hale, the experiments were readily made, thanks to the laboratory facilities available on the mountain.

The apparatus consists of a wide nickel tube, 60 cm long, the middle part of which is placed in an electric furnace, while the projecting ends are cooled by jackets with flowing water. The tube contains a few grams of sodium, and is permanently connected to a Geryk pump to remove the air and the gases which escape from the sodium during the first stages of the heating process. An arrangement is provided by which density-gradients of various known directions and arbitrary magnitude may be produced in the sodium vapor.

Sunlight coming from the mirror M (Fig. 1) of the Snow telescope, which has a focal length of 60 feet, passes through the tube T on its way to the slit S of the spectroheliograph. The distance between T and S is about 560 cm. A lens L_1 gives an image of the sun near the middle of the tube T. P is a diaphragm, with an adjustable slit, of which the lens L_2 projects an image in the plane of the diaphragm Q. Just behind the latter is a lens L_3; in combination with L_2 this forms an image of a section of the tube in the plane of the slit S of the spectroheliograph. In this image (Fig. 2) the rectangular window

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[1] *Astrophysical Journal*, 25, 95, 1907.

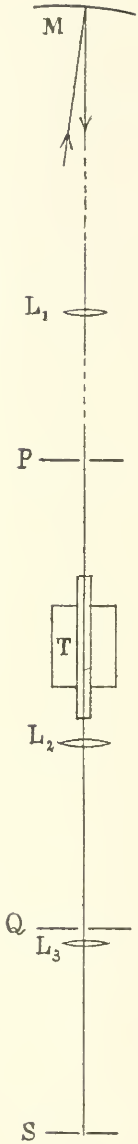

Fig. 1

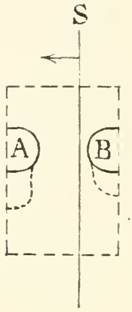

Fig. 2

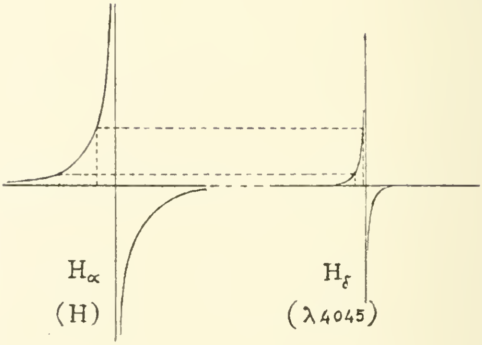

Fig. 3

of the caps of the tube[1] will of course come out with somewhat blurred edges, as only the middle section would show sharp. In *A* and *B* are projected the narrow nickel tubes for producing the required density-gradients. Their temperature may be varied at pleasure for this purpose by forcing an electric current or an air current through either of them. Cooling one of these tubes by an air current causes sodium vapor to condense on it; so in course of time drops of molten metal will hang on the tube, and fall off again.

When a photograph is made, the first slit *S* of the spectroheliograph moves across the image in the direction of the arrow, and at the same time the second or camera slit moves across the photographic plate.

Let us suppose the openings in *P* and *Q* (Fig. 1) to be so adjusted, that the image of the slit in *P* exactly coincides with the slit in *Q*. Then all of the light which passes through *P* and traverses the vapor along straight lines is transmitted by *Q*, and therefore contributes to the intensity of the image of the tube section. Waves, however, that deviate so much in the sodium vapor as to be intercepted by the screen *Q*, will be absent from the spectrum of the transmitted light.

If the furnace is slowly heated to 380° or 390°, the density of the vapor is pretty uniform in the middle part of the wide tube, and falls off toward the ends; but as the direction of the density-gradient nearly coincides with that of the beam of sunlight; even the waves subject to anomalous dispersion will hardly deviate from the straight path. The D lines in the spectroheliograph retain nearly their normal appearance. If now we blow air through the tube *B*, density-gradients are produced all around it in directions perpendicular to the axis of that tube. The D lines no longer show the same appearance throughout the field. In the spectrum of those parts of the field where perceptible gradients occur, the D lines then appear winged; they are indeed enveloped in *dispersion bands*. As the width of these bands depends on the magnitude of the gradient, it will, in our case, vary along the lines, and reach a maximum at the place in the spectrum which corresponds to the plane passing through the axes of the tubes *A* and *B*. With increasing distance between *S* and *B* (Fig. 2) the width of the bands will diminish.

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[1] Compare *Astrophysical Journal*, **25**, 97, 1907. Figs. 1, 2.

Let us consider the monochromatic images of the tube-section produced by the spectroheliograph if the camera slit is set at different distances from the D lines.

With the second slit at λ 5850, outside the region of the dispersion band of D_2, the illumination of the field is uniform (Plate XXX, *a*); nothing is visible of the density-gradients existing around the cooled tube *B*, because light of this wave-length travels along straight lines through the vapor.

Proceeding to λ 5870, we still are at such a distance from D_2 that the value of $\frac{1-n}{\Delta}=R$ (*n* representing the index of refraction, Δ the density of the vapor) is moderate. Steep gradients of the density are required to make the rays deviate sufficiently to miss the slit in *Q*, and such gradients are only to be found very near the surface of the tube *B*. We therefore obtain the image β, in which *B* appears surrounded by a narrow dark region.

The third photograph, γ, was made with λ 5877. For these waves the expression $\frac{1-n}{\Delta}$ is greater than for λ 5870, so that smaller values of the gradient suffice to give the rays a perceptible incurvation. The result is a broader dark region all around *B*.[1]

The photographs δ and ϵ were secured with the second slit on λ 5881 and λ 5885 respectively. This time the tube *A* was cooled instead of *B*. We see the dark aureole grow as the wave-length we are using approaches $\lambda_{D_2}=5890$. Getting nearer still, the whole field would finally become dark.

Similar results are obtained if we approach D_1 from the side of the *greater* wave-lengths, thus using waves for which $\frac{n-1}{\Delta}$ has increasing values.

By a slight change in the arrangement of our experiment we may obtain the opposite effect, to wit, that merely rays suffering anomalous refraction enter the spectroheliograph, while the normally refracted light is prevented from reaching the slit. We have only to make the slit in *P* very wide, and to put a vertical bar (a match, for instance) in the middle of it, the image of which now falls exactly

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[1] In this image the lower right corner was cut off by a rubber tube accidentally crossing the path of the beam.

PLATE XXX

Density-Gradients in Sodium Vapor as Shown by the Spectroheliograph

on the slit in Q. Under these circumstances light, issuing from the divided opening in P, can be transmitted by Q only if it has been deflected in the vapor. In this way the photographs ζ, η, θ were obtained, the second slit being set on λ 5884, λ 5886, λ 5888 respectively. If there had been no density-gradients, the whole field would have shown dark; the *bright* regions, however, now prove the existence of the gradients. When taking ζ and η, the tube B, and when taking θ, the tube A, was cooled.

The following general statement is borne out by these experiments.

If an illuminated absorbing vapor is investigated by means of the spectroheliograph, and the camera slit of the instrument is set *on the edge* of a dispersion band, marked irregularities in the brightness of the field will only appear at those places in the image which correspond to regions with *large* density-gradients in the vapor. Setting the slit *nearer the middle* of the dispersion band, we shall get evidence, in the image, also of the regions with *smaller* gradients, etc. Particulars regarding the distribution of a vapor are thus clearly shown by the spectroheliograph through anomalous refraction, even in cases where the absorbing or emitting power of that medium would have failed to reveal its structure.

The bearing of these inferences on astrophysical phenomena may now be considered a little more closely.

Suppose we have a large mass of absorbing vapor of such average density that, if it were uniform, its absorption lines would appear rather narrow; and of such temperature, and condition of luminescence, that its emission lines are very faint. As soon as the density of this mass becomes irregular, some parts of it may give rise, when traversed by light from another source, to the appearance of dark or bright dispersion bands, greatly exceeding in width and strength its absorption or emission lines.

It is therefore *possible* that anomalous refraction plays a very important part in the production of those phenomena which the student of astrophysics observes with his spectroscope or spectroheliograph; we must inquire how far this is also *probable*.

One might be inclined to object, for instance, that in our experiments the use of a narrow and sharply limited source of light, placed at a fair distance behind the vapor, seemed to be a necessary condition for obtaining any marked dispersion effects, and that in the sun similar circumstances are very unlikely to prevail. Indeed, the body of the sun, whatever the nature of the photosphere may be, is a large incandescent mass, closely surrounded by the absorbing vapors, so that the "source of light," if considered from a point of the chromosphere, subtends a solid angle of nearly 2π. The reversing layer and the chromosphere have sometimes been compared to a thin, transparent layer of selectively absorbing varnish, covering a luminous (e. g., phosphorescent) globe: the photosphere. It seems very improbable that refraction in density-gradients of such a transparent envelope should be able to disturb to any perceptible degree the uniform brightness of that globe.

The comparison, however, is entirely misleading, because, so far, an essential relation between absolute size and density-gradients is overlooked in it. But if carried through properly, it will lead us to the opposite conclusion, namely, that refraction in the solar atmosphere must greatly alter the distribution of the light on the disk.

If we wish to form an image, on a reduced scale, of the sun considered as a refracting body, we have to reduce the radii of curvature of the rays in the same proportion as we do the diameter, for instance 10^{10} times (so as to make the diameter of the photosphere 14 cm).

By the general equation

$$\frac{d\Delta}{ds}=\frac{1}{R\rho}\text{[1]} \qquad (1)$$

we know that, for a given value of the refraction constant R, the radius of curvature ρ of a beam of light is inversely proportional to the density-gradient $\frac{d\Delta}{ds}$ in the direction toward the center of curvature. In our image, therefore, the density-gradients have to be taken 10^{10} times as great as they are in the sun.

Let us suppose that at a certain level in the solar atmosphere irregular density-gradients occur, that are of the same order of magnitude as the radial (vertical) density-gradient in our earth's atmos-

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[1] *Astrophysical Journal*, 25, 107, 1907.

phere, viz., 16×10^{-10}.[1] At the corresponding points in our image we then have to put $\frac{d\Delta}{ds}=16$. If the layer of "varnish" were really traversed by many density-gradients of this order of magnitude, it would be very different from ordinary transparent varnish, and certainly be able to disturb the uniform brightness of the background, somewhat like a layer of glass beads or swollen sago grains. Even normally refracted waves would perceptibly deviate in an envelope of this kind. For if in our equation (1) we put $\frac{n-1}{\Delta}=R=0.5$ and $\frac{d\Delta}{ds}=16$, we get $\rho=0.125$ cm, so that the average curvature of such rays is already sufficient for producing sensible changes in the divergence of beams on their way through a shell not thicker than 0.1 cm.

Waves suffering anomalous refraction will of course be much more scattered by the same medium. Let us consider an absorbing substance which, at a certain level, occupies say only 1 per cent. of the solar atmosphere, taken as a perfect mixture. Its density-gradients will then be only $\frac{1}{100}$ of those of the mixture. The refraction constant, on the other hand, for waves near one of its absorption lines may attain values as high as 1000 or 2000. With $R=1600$ (observed in sodium vapor, *Astrophysical Journal*, **25**, 108, 1907) our equation (1) becomes

$$\frac{1}{100}\frac{d\Delta}{ds}=\frac{1}{1600\rho}\,.$$

In a level where in our image the irregular density-gradients of the envelope were supposed to have an average value $\frac{d\Delta}{ds}=16$, the equation gives

$$\rho=0.004\text{ cm}.$$

It is evident that under such circumstances rays may easily deviate 90 degrees and more in the thin shell of transparent matter covering our globe, and thus give rise to a very unequal distribution of the light in photographs of it, secured with the spectroheliograph.

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[1] The frequent occurrence of density-gradients nearly perpendicular to the radii of the sun is rendered more probable still since increasing evidence has been obtained by Professor Hale of the existence of solar vortices, in which the convection currents (especially in sun-spots) are sufficiently strong to produce magnetic splitting of absorption lines. (Cf. *Nature*, **78**, 368–370, Aug. 1908).

This conclusion holds quite as well with regard to the real sun. It follows directly from our *only* assumption that in some level of the sun there exist irregular density-gradients comparable in magnitude with the vertical gradient in the earth's atmosphere. At lower levels greater gradients, at higher levels smaller gradients, may then be expected to prevail. As the validity of this assumption can hardly be doubted, we may infer that the existence of some important influence of anomalous dispersion on astrophysical phenomena is not merely possible, but *exceedingly probable,* in spite of the absence of narrow slits as sources of light.

Although we are free to admit that the phenomena observed with the spectroheliograph on the solar disk are in part due to absorption and selective radiation, dependent on various conditions of temperature or luminescence, we may nevertheless inquire into some consequences to which one is led if only the effects of refraction in a mixture of vapors are considered.

The composition of the solar atmosphere cannot be the same at all levels. As we get lower, the percentage of heavier molecules is likely to increase; but we should not presume too much as to the order in which the elements will come into evidence, on account of possible condensation, and because the pressure of radiation counteracts gravitation to a degree that depends on the size of the particles, and, therefore, on numerous unknown conditions prevailing in the sun.

Yet for each element a certain level must exist, in which its percentage in the mixture is a maximum. Accordingly, the refracting properties of successive layers will be governed by different elements. A photograph, made with the spectroheliograph in a hydrogen line, shows a structure which of course depends on the distribution of all the hydrogen present in the successive layers, but is chiefly determined by the density-gradients in a rather high level; whereas a photograph made with an equally strong iron line reveals especially the structure of lower regions. This explains the difference in character between iron and hydrogen plates.

It must be possible, on the other hand, to obtain almost identical photographs with different lines, provided they belong to the same element, or to elements that are most in evidence at about the same level of the sun; but then another condition has also to be fulfilled, viz., that the camera slit transmit rays of the same refrangibility in both cases. If, for instance, Fig. 3 represents the dispersion curve near $H\alpha$ and near $H\delta$, the width and the position of the camera slit ought to be so chosen as to let in only waves corresponding to parts of the curve inclosed between equal ordinates in the two dispersion bands.[1]

Recently it has been found by Hale and Ellerman that, while $H\beta$ and $H\gamma$ and $H\delta$ lines give very similar results, photographs with the much stronger $H\alpha$ line are widely different in some respects. Bright flocculi appear on these plates at points where no corresponding objects are shown by $H\delta$. Moreover, the dark $H\alpha$ flocculi, while showing a general agreement in position and form with those of $H\delta$, are stronger and more extensive. In some instances, however, small areas appear dark in $H\delta$ which are absent or fainter in $H\alpha$.[2]

Such differences seem to be of the same character as those observed between photographs made with the slit in the broad calcium bands H or K at various distances from the central line. They may find a similar explanation if we assume that the average rays used in the $H\alpha$ photographs were refracted to a higher degree than those used in the $H\delta$ photographs, but both by the same density-gradients. It is not improbable, therefore, that in the wings of $H\alpha$ waves may be selected so as to give spectroheliograph results closely resembling $H\delta$ plates.

That also lines of different elements may give very similar results with the spectroheliograph, is exemplified by the case of calcium and iron. Among the beautiful collection of photographs secured on Mount Wilson I saw several iron (λ 4045) plates resembling certain

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[1] Waves lying about symmetrically on either side of an absorption line, and answering the relation $n-1=1-n'$ between the indices of refraction n and n' of the medium for them, must give nearly the same spectroheliograph results on the greater part of the disk. This follows from a discussion of the various possibilities regarding the relative position of density-gradients and the source of light. Consequently an $H\delta$ plate, obtained with the camera slit centrally, so as to embrace the whole width of that rather narrow dispersion band, will scarcely differ, at first sight, from a photograph made with only one of the wings.

[2] *Memorie Soc. Spettroscopisti Italiani*, **37**, 99, 1908.

calcium (H_1) plates of the same daily series rather closely. As the atomic weights of calcium and iron are not so very different and their levels of maximum density therefore probably not far apart, the refraction caused by these elements may bring out the density-gradients of nearly the same layer of the solar atmosphere. It will do so by a similar distribution of the light in the two photographs—provided that rays of the same refrangibility are used in both cases. And this condition may be fulfilled by setting the camera slit on corresponding regions of the spectrum, in the manner as illustrated by Fig. 3, if we imagine it now to bear on the calcium (H) line and the iron line.

With a calcium and a hydrogen line such similarity could not be found.

Far more evidence will of course be required before we shall be able to decide whether or not anomalous dispersion is the principal agent in determining the flocculent appearance of the solar disk. Plates secured with many lines of various elements should be compared. The powerful 30-foot spectroheliograph of the "tower telescope" of Mount Wilson is excellently adapted for work of this kind, not only on account of its great dispersion, permitting the use of finer lines, but chiefly because it is provided with three camera slits, so that perfectly simultaneous photographs with different lines may be secured. By this arrangement, really comparable monochromatic pictures of the sun may be obtained, since the otherwise confusing influence of the variable refraction in our atmosphere is thus rendered harmless.

I feel greatly obliged to Professor George E. Hale for having procured me the opportunity of making an investigation at the Mount Wilson Solar Observatory, but more still for his keen and stimulating interest in the problems suggested by the application of the principle of anomalous refraction to astrophysics. I am also very much indebted to the kindness of Mr. F. Ellerman, Mr. W. S. Adams, and Dr. C. M. Olmsted for valuable information and assistance in connection with the inquiry here reported upon.

UTRECHT
August 1908

THE EMISSION SPECTRUM OF SILVER HEATED IN A CARBON-TUBE FURNACE IN AIR

By W. GEOFFREY DUFFIELD and R. ROSSI

Some work by one of us upon the effect of pressure upon arc spectra[1] demanded a more complete knowledge of the band spectrum of silver than was available, so it was decided to utilize the method for the production of spectra which had been successfully used by A. S. King[2] for many other metals, namely, the carbon-tube furnace method.

The furnace employed consisted of a carbon tube 12 inches long and $\frac{5}{8}$ inch in diameter, whose ends were fitted tightly into holes in two heavy graphite bars which served to keep them fairly cool and to feed the tube with current. The tube was surrounded with powdered carborundum which prevented the air from reaching it and causing too rapid oxidation. One end was closed by a mica window through which visual observations could be made, while the other, opposite which was placed the 1-meter grating spectrograph, was left open. To prevent light from the walls of the tube from entering the spectrograph directly, two small diaphragms, each with an aperture about one-fourth the internal diameter of the furnace-tube, were placed in line with the furnace, and between it and the grating a lens then focused the narrow beam of light upon the slit of the instrument. It was a matter of indifference whether the lens was focused for infinity or for the center of the tube. Upon heating the tube and examining its image upon the slit, the continuous spectrum from the walls was seen to extend gradually toward the center until the axis of the tube appeared white hot. Precisely why this should occur is not clear, but the explanation may be sought for either in something resembling a flame resulting from the union of the heated carbon with the oxygen of the air or in the refraction of light as it passes through layers of heated air of varying densities and temperatures. Examined

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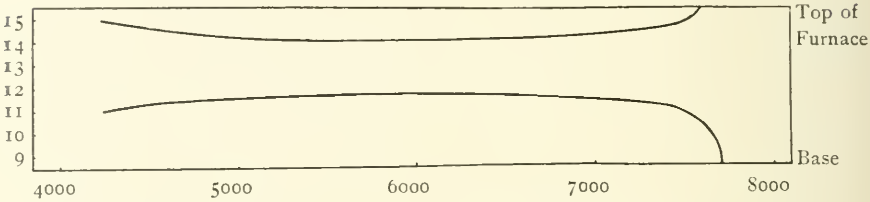
[1] Duffield, *The Observatory*, **31**, 293, 1908.

[2] *Astrophysical Journal*, **21**, 236, 1905; **27**, 353, 1908.

through the spectroscope, the extension toward the center was seen to be a function of the wave-length of the light examined.

Measurements were made of the distances to which the continuous spectrum extended from the top and bottom of the furnace at a given current (102 amperes) and they are plotted as ordinates in the accompanying diagram,[1] which has been carefully drawn to scale.

The metal to be examined was introduced in a small graphite trough, about an inch long and a quarter of an inch deep, which had been hollowed out sufficiently to carry a few small pieces of the metal. The trough was carefully pushed into the center of the furnace. In the case of silver, the spectrum continued only so long as there was metal in the trough, the vapor probably condensing upon the cool ends or escaping from the open end of the tube.



The carbon tubes were not free from impurities, and some preliminary visual work upon their spectra was necessary. They did not prove as troublesome as was anticipated, because, with the exception of the D lines, the *Li* line λ 6708, and a band at 6118, they required a higher temperature for their production than did the silver spectrum. Almost all the impurity lines were sharp and therefore easily distinguished from the diffuse silver lines. A record was kept of the order in which the impurity lines appeared as the current was gradually increased, and this proved useful in distinguishing the true silver spectrum.

VISUAL OBSERVATIONS

Visual observations were made upon the genesis of the silver spectrum and its behavior as the current through the tube was increased. An example is here given.

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[1] The degree to which the eye is sensitive to the different colors influences the shape of this curve; its edges are sharper toward the red end of the spectrum.

TABLE I

Time: Mins.	Amperes	Observations
8	97	D Lines (*Na*)
9	105	6708 (*Li*)
		6118 (Impurity). Violet head of band
12	110	Weak continuous spectrum from 4996 to violet upon which are superposed bands:
		4669 (*Ag*) center
		4616 (*Ag*) center
		4563 (*Ag*) center
		4519 (*Ag*) center
		4469 (*Ag*) center
		4996 (*Ag*) strong diffuse line
		5022 (*Ag*) strong diffuse line
16	112	5050 (*Ag*) weak line
		4970 (*Ag*) weak line
27	132	Lines stronger, continuous spectrum more pronounced; 4996 resembles head of band fading into violet
35	135	Bands distinguishable further toward violet:
		4438 (*Ag*) center
		4360 (*Ag*) center
38	138	Continuous spectrum stronger, masking bands above trough. In the lower part of the tube the trough forms a background of continuous spectrum and in this lower part the silver spectrum gradually reverses as the amount of vapor increases
43	140	4996 (*Ag*) reversed
46	155	Bands reversed:
		4469 4516 4560 4614 Centers of dark parts, these coincide with centers of bright emission bands at 110 amperes 4452 4493 4539 4592 4648 Centers of bright parts
		Continuous spectrum (above trough) extends from 5062 to the violet
		All silver lines are reversed
56	160	Impurity lines appear first
58	180	Many more impurity lines appear
60	205	*Ag* lines vanish but bands still seen reversed
		New heads of bands appear:
		4293 (*Ag*) red head of bright band
		4322 (*Ag*) red head of bright band
		4389 (*Ag*) red head of bright band
		4426 (*Ag*) red head of bright band
		Also seen in one experiment:
		6200? center of bright band
		6300? center of bright band
		6470? center of bright band
63	210	Silver bands vanish. Continuous spectrum strong
67 68	212 0	Silver spectrum does not reappear during the cooling of the tube

It will be seen from the above, which is one of many experiments which agree admirably with one another, that both the emission and the absorption spectra have been examined and that the centers of the bright bands of the former are, within the errors of the measurements, coincident with the centers of the dark bands of the latter. In the absorption spectrum appear the red heads of bright bands which appear on the photographs as violet heads of bright bands in the emission spectrum; they have only once been observed visually. The visual observations are comprised in the following table, which is that of the emission spectrum. The absorption spectrum seems to be its exact complement.

TABLE II

Emission Spectrum of Silver (Visual)

Bands				Lines
No. of Readings	λ	Description	Distances apart	
	4293*	violet head		4970 weak
	4322*	violet head		4996 strong and diffuse
5	4360	center		5022 strong and diffuse
	4389*	violet head		5050 weak
	4426*	violet head	78	
4	4438	center	31	
7	4469	center	50	
6	4519	center	44	
4	4563	center	53	
10	4616	center	50	
6	4669	center		
1	4822 ?	violet head		
1	4876 ?	center		

* Not seen as violet heads of bands in emission spectrum but as red heads of bands in absorption spectra. Measurements agree well with those made photographically. These bands are not resolved on the photographs.

PHOTOGRAPHIC OBSERVATION

Several photographs have been taken with the arrangement described—in each case the continuous spectrum from the graphite trough was avoided and the photographs were those of the emission spectrum.

The dispersion was greater than that used for visual work and considerable detail appears upon the plates. Spectra were photographed in the second and in the first order. Iron comparison spectra were photographed alongside to assist the work of measuring the plates, the use of a comparison shutter was avoided: the center of the slit was covered when the iron arc was photographed.

The wealth of lines led us to suspect that the spectrum was not due to silver alone, but photographs taken with other metals in the

TABLE III

No. of Photographs	No. of Readings	Description	Wave-Length	Intens.	Previous Measurements Oxyhydrogen Flame Spectrum
1	2	Hazy line	4099.5	1	4091.0 (Hartley)
1	2	Hazy line	4107.1	1	4102.0 (Hartley)
1	4	Hazy line	4114.1	1	
1	4	Hazy line	4120.8	1	
1	4	Hazy line	4129.3	1	
1	4	Hazy line	4137.1	1	
1	4	Hazy line	4145.6	2	4147.4
2	6	Hazy line	4152.6	2	
2	4	Hazy line	4160.5	2	4156.4 (Hartley)*
2	4	Hazy line	4169.0	2	
2	6	Hazy line	4177.4	2	4176.4
2	4	Hazy line	4186.0	2	
2	6	Hazy line	4194.3	2	
2	4	Hazy line	4204.4	2	
2	4	Hazy line	4212.2	2	
2	6	Hazy line	4221.4	3	
2	4	Hazy line	4229.8	3	
2	6	Hazy line	4239.5	3	4231.0 4238.2 (Hartley) 4244.9
2	6	Hazy line	4248.0	3	
1	4	Hazy line	4258.7	3	4258.0 11th band (Hartley)
2	4†	Violet edge of band	4266.6	3	
1	2	Violet edge of band	4273.9	1	4273.9
2	6†	Violet edge of band	4294.9	4	4283.2 10th band 4294.7 (Hartley)
2	4†	Violet edge of band	4322.2	5	4300.5 9th band 4330.9 (Hartley)
2	4	Hazy line	4336.5	3	
2	4	Hazy line	4344.5	3	4347.0 8th band (Hartley)
2	6	Hazy line	4352.2	3	
2	6	Center of shaded portion 4360	4358.8	3	4360.7
2	6	Hazy line	4368.3	2	4373.5 7th band
2	6†	Violet edge of band	4387.5	5	4396.2 (Hartley)
2	6	Hazy line	4403.5	3	
2	6	Hazy line	4409.1	3	4408.6 6th band
2	6†	Violet edge of band	4423.8	4	4424.8 (Hartley)
1	6	Hazy line	4432.8	3	
1	4	Center of shaded portion 4438	4445.9	1	
2	8	Hazy line	4453.4	3	4449.8 5th band (Hartley)
2	6	Hazy line	4461.5	4	
2	6	Center of shaded portion 4469	4469.1	4	4470.9
					4475.1 (Thalén)
2	6	Hazy line	4498.7	4	4490.9 4th band (Hartley)
2	6	Hazy line	4505.1	5	
1	6	Hazy line	4512.7	6	
1	4	Center of shaded portion 4519	4520.0	3	4519.0
1	2	Hazy line	4537.2	1	4533.4 3d band (Hartley)
2	6	Hazy line	4543.1	3	
2	6	Hazy line	4550.1	5	
2	6	Hazy line	4556.6	5	
1	4	Center of shaded portion 4563	4564.5	6	4563.4

†Also observed visually.

* *Phil. Trans.*, 185, 195, 1894.

TABLE III—*Continued*

No. of Photographs	No. of Readings	Description	Wave-Length	Intens.	Previous Measurements Oxyhydrogen Flame Spectrum
2	6	Hazy line	4570.8	3	4570 (L. de Boisboudran)
1	4	Hazy line	4583.0	2	
1	4	Hazy line	4588.6	3	
2	8	Hazy line	4594.9	5	4591.0
2	6	Hazy line	4600.8	6	2d band
2	6	Hazy line	4607.8	6	(Hartley)
2	6	Hazy line	4613.6	5	
2	6	Center of shaded portion 4616	4619.3	3	4616.5
1	2	Hazy line	4628.1	1	4622 (L. de Boisboudran)
1	2	Hazy line	4633.1	1	
2	8	Hazy line	4637.6	3	
1	4	Hazy line	4643.5	2	
2	4	Hazy line	4650.8	1	4650.8
2	6	Hazy line	4657.2	3	
1	4	Hazy line	4663.0	5	1st band
1	4	Center of shaded portion 4669	4668.9	5	4669.0 (Hartley)
1	4		4688.8	2	(L.deB)
1	4	Hazy line	4700.7	2	4696.0
1	2†	Violet edge of band	4819.9	1	
1	2†	Hazy line	4970.01	10	
1	2†	Hazy line	4996.14	20	Hartley mentions three lines in the green region but they were too faint to be measured
1	2†	Hazy line	5022.58	15	
1	2	Hazy line	5028.89	5	
1	2†	Hazy line	5050.57	8	

† Also observed visually.

furnace have not yielded spectra in the least similar and the photographs do not differ from one another in any respect save in their densities; the silver used was obtained from the chloride and called chemically pure.

Some faint resemblance between the heads of silver bands and those of the flame spetrum of tin led us to suspect the presence of this metal, but pure tin placed in the electric furnace gave no lines or bands even when heated to a temperature higher than that required for the production of the spectrum of silver. Other metals were also introduced but they gave no spectrum at all resembling the one under discussion.

The general appearance of the silver photographs is that of a banded spectrum consisting of a number of hazy lines closely spaced, superposed upon a shaded background, which forms the main part of the visual spectrum; the estimates of the intensities were made with difficulty, as these shadings gave fictitiously large intensities to those lines which fell where the shadings were dark. With the exception of the five green lines at λ 4970, 4996, 5022, 5029, 5050, the lines appear spaced with a certain amount of regularity which suggests that they are members of a banded spectrum. Table III contains a list of the lines and heads of bands capable of measurement on the photographs. The error should not be as great as 0.4 Å. U. for any of the lines except λ 4352, 4368, 4433, 4461, 4571, for which it may be as large as 0.8 Å. U.

FLUTINGS OF DOUBTFUL ORIGIN

Besides the spectrum which has been described, a second series of flutings of doubtful origin in the region 5370 to 5750 appears upon two of the photographs of silver but they have not been visually observed though a careful watch has been kept for them during several subsequent experiments with that metal. One of us while examining the impurities in an empty tube saw some flutings flash out in this region of the spectrum but they vanished before any measurements of their positions could be made. The following are the wave-lengths of the centers of the broad flutings which are approximately 15.6 Ångström units apart; their widths are about the same as their distances apart. These flutings are perhaps identical with the very diffuse banded structure noticed by King to the red of λ 5500 when water vapor was present in an otherwise empty tube.

TABLE IV

Fluted Spectrum of Doubtful Origin (Emission Spectrum)

Mean values of two readings

5373.0
5387.1
5402.1
5416.3
5433.7
5447.2
5464.5
5478.5
5495.3
5510.4
5524.7
5540.9
5556.3
5571.9
5597.3
5604.0
5616.7
5636.8
5650.8
5668.7
5683.9
5699.7
5716.9
5732.4
5749.6

None of the strong lines in the green here obtained occurs in the arc or spark spectrum of silver. Nor have these lines been measured in the oxyhydrogen flame though Hartley saw three faint ones in that region. The nearest line to any of them is at 4993.2 noticed by Kayser and Runge as a feeble arc line of intensity =6. The oven spectrum of silver thus differs markedly from the spectra of silver produced by other methods.

We acknowledge with pleasure our indebtedness to the papers of A. S. King (to which reference has already been made) and express our thanks to Professor Rutherford for having placed the necessary apparatus at our disposal.

The Physical Laboratories
Manchester University
August 25, 1908

ON THE POSSIBLE EXISTENCE OF STEAM IN THE REGIONS OF SUN-SPOTS

By A. L. CORTIE

In a previous communication,[1] the probability of a lower temperature in the regions of sun-spots relatively to that of the photosphere, was derived from a comparison of the behavior of the bands of titanium oxide in the spectrum of *Mira Ceti*, at a more and a less brilliant maximum, and the bands of the same chemical compound in the spectrum of sun-spots. In the present paper the question raised is whether the reduction of temperature over such regions is sufficiently great to permit the formation of water-vapor, obviously in the form of super-heated steam. Observations of the widening of lines marked as telluric in Ångström's map in earlier observations, and as due to aqueous vapor in Rowland's catalogue for later observations, have been repeatedly made at Stonyhurst during the last twenty years.[2]

In the earlier observations particular attention was called to widened telluric lines included in the regions λ 5940 and λ 5944. The explanation advanced to account for many, if not for most, of these widenings, was, that they were due to the existence of faint solar lines in the vicinity of the aqueous vapor lines, which could not be separated from such lines with the dispersion employed. The approximate purity of the spectrum in the Browning twelve-prism spectroscope for this region is about 24,000. The instrument was used with object-glasses of 8 and 15 inches. With the more powerful combination of the Princeton Observatory, Dr. Mitchell was unable to observe these lines. Referring to my observations of the widening of telluric lines he remarks:

> The writer has never observed these lines affected either before or after their publication, although they have been given a careful examination. In regard to the few vapor lines in the table (his table), the writer doubts whether they are due solely to water-vapor. They may possibly be solar lines, unidentified

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[1] *Astrophysical Journal*, 26, 123, 1907.

[2] E. g., *Memoirs R. A. S.*, 20, 55, 1892; *Astrophysical Journal*, 20, 253, 1904.

> as yet, due to elements having lines accidentally coincident with the water-vapor lines, the widening being due to the solar line.[1]

This weighty testimony in an adverse sense from so acute an observer must be taken into account in the discussion which follows. The observations now detailed were made with the large grating spectrometer constructed by Mr. Hilger. The collimator and observing telescope of this instrument have each a 3-inch object-glass of quartz, the focal length of which is 24½ inches. The grating 3¼ by 1$\frac{15}{16}$ inches is one of Rowland's highest grade. The number of lines to the inch is 14,438. The image of the sun on the slit was formed by a 4-inch object-glass and an enlarging lens. With this instrument a very good negative of the spectrum of the large sun-spot, Greenwich number 5933, was obtained on July 31, 1906, in the third order in the region contiguous to the D lines. A positive made from this negative has been carefully studied under the microscope of the Hilger measuring machine, the wave-lengths of such lines as could not be identified with certainty on the excellent maps of Mr. Higgs being determined by measurements on the machine. These lines have the prefix *c* in the table. The portion of the spectrum studied is from D_1 to λ5953.386, roughly 50 Ångström units, in a region which is crowded with water-vapor lines. The study is very far from being exhaustive of all water-vapor lines which have been noted as widened in former communications. Its object is to see whether in this limited portion of the spectrum, with the greater dispersion at present employed in such researches, there are any water-vapor lines which are undoubtedly widened in sun-spots. Other details of the examination of this part of the spectrum with regard to the metallic lines are also set forth in the table.

With the exception of a few metallic lines, lines which on examination were found to be unaffected in sun-spots have not been entered in the table. Of 91 lines examined 64, or 70.3 per cent., are due to water-vapor, and of these 64, 29, or 45.3 per cent., were affected in the sun-spot either as widened or darkened lines. On comparing these lines with the same lines as recorded on the photographic map of the sun-spot spectrum, so kindly distributed by Professor Hale and Mr. Ellerman to the co-operating observers of the International

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[1] *Astrophysical Journal*, **22**, 29, 1905.

TABLE I

Lines between D_1 and λ 5954 in the Spectrum of a Sun-Spot

	Wave-Length	Origin	Solar Intensity	Spot Intensity	Remarks
	5896.3 7	*Na*	20		Winged, on violet side 0.66, on red side 0.58, unsymmetrical
	96.710	A (*wv*)	1	3	Extends over penumbra
	97.047	A (*wv*)	2	3	Extends over penumbra
	97.677	A (*wv*)	0	1	H and E
	99.215	A (*wv*)	2	3	
	99.518	*Ti*	1	4	
	5901.140	A (*wv*)	00	0	
	01.682	A (*wv*)	6	6	
	02.694	*Fe*	0		Weakened
	03.748	A (*wv*)	1		Darkened. H and E
c	04.350			2	Rowland .420
c	04.782			0	Spot-band. Rowland .850
	05.895	*Fe*	4	6	
	06.505	A (*wv*)	000		Spot-band. H and E
	07.060		0	1	
	07.475	A (*wv*)	0	1	H and E
	08.070	A (*wv*)	1	2	H and E
	08.425	A (*wv*)	1	2	
	09.213	A (*wv*)	3	4	H and E
	09.668	A (*wv*)	00	0	
	10.197	*Fe*	1	2	
	10.398	A (*wv*)	1	2	
	10.987	A (*wv*)	2	4	H and E
	11.791			0	Spot-band. Rowland 11.81
	12.228	A (*wv*)	00		Darkened. H and E
	13.212	A (*wv*)	3		Slightly darkened. H and E
	14.335	*Fe*	4		
	14.430	A (*wv*)	6		Weakened. Winged 1.3 units, due to *Fe* line
	16.475	*Fe*	3	4	
	17.605	A (*wv*)	0	1	Extended into penumbra
	18.635	A (*wv*)	4		
	18.773	*Ti*	0	5	Widening due to titanium
	19.276	A (*wv*)	5	5	
	19.860	A (*wv*)	7		Widened on red side. H and E
	22.334	*Ti*	0	4	Extended far beyond penumbra
	23.405	A (*wv*)	00	1	
	24.490	A (*wv*)	4		Widened on violet side
c	26.252				Spot-band. Rowland .244
	26.835	A (*wv*)	000		Spot-band. H and E
	28.013	*Fe*	2		Weakened
	29.898	*Fe*	2	4	
	30.815	A (*wv*)	00		Spot-band. H and E
	31.230	A (*wv*)	00		Spot-band by side of line
	32.306	A (*wv*)	5	6	H and E
c	33.878				Spot-band. Rowland .872 A (*wv*)
c	34.334				Spot-band. Rowland .300 A (*wv*)
	35.400	A (*wv*)	00	0	
c	36.970			0	Spot-band, not very marked. Rowland 37.183
c	37.486			2	Rowland .523 A (*wv*)
	38.270	A (*wv*)	0	1	H and E
c	38.779			1	Spot-band, extending beyond penumbra. Rowland .810 A (*wv*)

TABLE I—*Continued*

Wave-Length	Origin	Solar Intensity	Spot Intensity	Remarks
c 39.524			1	Spot-band, extending beyond penumbra. Rowland .455 A (*wv*)
41.985	*Ti*	00	2	
c 44.428			2	
44.530	A (*wv*)	1	2	Spot-band, slightly more refrangible
44.945	A (*wv*)	1	1.5	H and E
45.463	A (*wv*)	00	2	Spot-band against line slightly more refrangible
c 46.455				Spot-line. Rowland .485
c 48.239				Spot-band. Rowland .195
48.765	*Si*	6	6	
49.566	*Fe*	1	2	
50.560	A (*wv*)	0	1	
c 51.100			0	Spot-line. Rowland .070
51.718	A (*wv*)	0	1.5	Winged. H and E
52.943	*Fe*	4	4	
53.386	*Ti*	1	2	

Solar Research Union, it is found that 16 of these 29 lines are on the map as widened or darkened lines. Such lines are marked in the column of remarks by the letters H and E. In this map the sun-spot spectrum was isolated from the photospheric spectrum, which was not the case in the Stonyhurst photographs studied, on account of the smallness of the sun's image. Particularly noticeable is the region λ 5906–9 on the map, in which the water-vapor lines are much darkened in the spectrum of the spot. At the same time the increased dispersion given by the Hilger spectrometer, and still more in the enlarged maps of Hale and Ellerman, shows that in many cases the widening attributed in my earlier papers to the aqueous vapor lines is due to very close solar lines. A good example is the close double, 5918.635 and .773, due respectively to water-vapor and to titanium, where the widening of the line is evidently due to titanium. Nevertheless the fact remains that with dispersions available up to the present, several lines of aqueous vapor, even in the limited part of the spectrum studied, are affected in sun-spots. In general the lines so affected are the fainter lines of the general solar spectrum, the more prominent water-vapor lines, obviously due to the absorption of our atmosphere, being unaffected. There are several instances in the table of the spot-bands being joined on to, or so contiguous to, vapor lines as to be inseparable with the dispersions employed.

Also several lines are noted as extending into the penumbra and beyond, a phenomenon to which attention was called in my earliest papers.

In a recent communication to the R. A. S. on "The Origin of Certain Bands in the Spectra of Sun-Spots,"[1] Professor Fowler demonstrated that a great number of these bands are due to the chemical combination magnesium hydride. This spectrum has been studied in the laboratory by Mr. E. E. Brooks,[2] who finds that "the mere presence of dry hydrogen is not sufficient to bring out the hydride flutings," and further on, that the spectrum "can be seen in the presence of a trace of water-vapor under conditions in which it would be totally absent without that vapor, a hydrogen atmosphere being present in both cases." In a word, Mr. Brooks finds that this spectrum of magnesium hydride, so prolific according to Professor Fowler in the band spectrum of sun-spots, cannot be produced in the laboratory without the presence of water-vapor. Such evidence greatly enhances the possibility of the existence of steam in the regions of the sun containing the sun-spots. Doubtless the reduction of temperature, brought about by the expansion of the absorbing vapors giving rise to the appearence of a sun-spot, must be very great. The presence of oxygen in combination with titanium, and of hydrogen with magnesium, has already been ascertained, as constituents of the band spectrum of sun-spots. Under the greatly lowered temperature what is to prevent the combination of the hydrogen and oxygen to form steam?

STONYHURST COLLEGE OBSERVATORY
July 27, 1908

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[1] *Monthly Notices, R. A. S.*, **67**, 530, 1907.

[2] *Proc. R. S. A.*, **80**, 223, 1908.

PHOTOGRAPHIC OBSERVATIONS OF COMET *c* 1908 (MOREHOUSE)

SECOND PAPER

By E. E. BARNARD

In this *Journal* for November I have already described some of the outbursts of this comet. The two photographs there given showed the great disturbance of September 30. I shall here deal briefly with the remarkable outburst of October 15, which was quite different in appearance from that in September, as will be seen by comparing the present photographs with those in my previous paper. In the first case the matter that was thrown off did not go out as a mass, but instead it simply augmented the general strength of the tail. The supply slowly diminished until it was finally cut off altogether, thus separating the tail from the head. While this process was going on, the tail was narrowing down to a slender neck at the head, the whole having a twisted or cyclonic form. On October 15 it would appear that great masses were thrown off in an explosive form, and immediately afterward a new, straight tail was formed and ejected against the more bulky and slower-moving masses.

The photograph of October 14 shows that the comet at that time was becoming very active. It was throwing off volumes of matter which made the tail very strong, with heavy irregularities in it. This activity culminated in the convulsion that twelve hours later threw off the great masses seen on the photograph of October 15. These masses are strongly shown on the plate of the 16th but in a greatly altered and diffused form. They can still be seen on the plates of the 17th. They were changing very greatly on the photographs of the 15th, and at the same time were receding from the comet. In the first photograph of that date the new straight narrow tail joins on to the southern part of the irregular mass, which extends away from the comet in a broadening sweep to form the distant part of the tail. In the successive pictures the masses seemed to drift south faster than the comet, so that in the last pictures of that night the tail joined the middle of the mass, the rear edge of which was

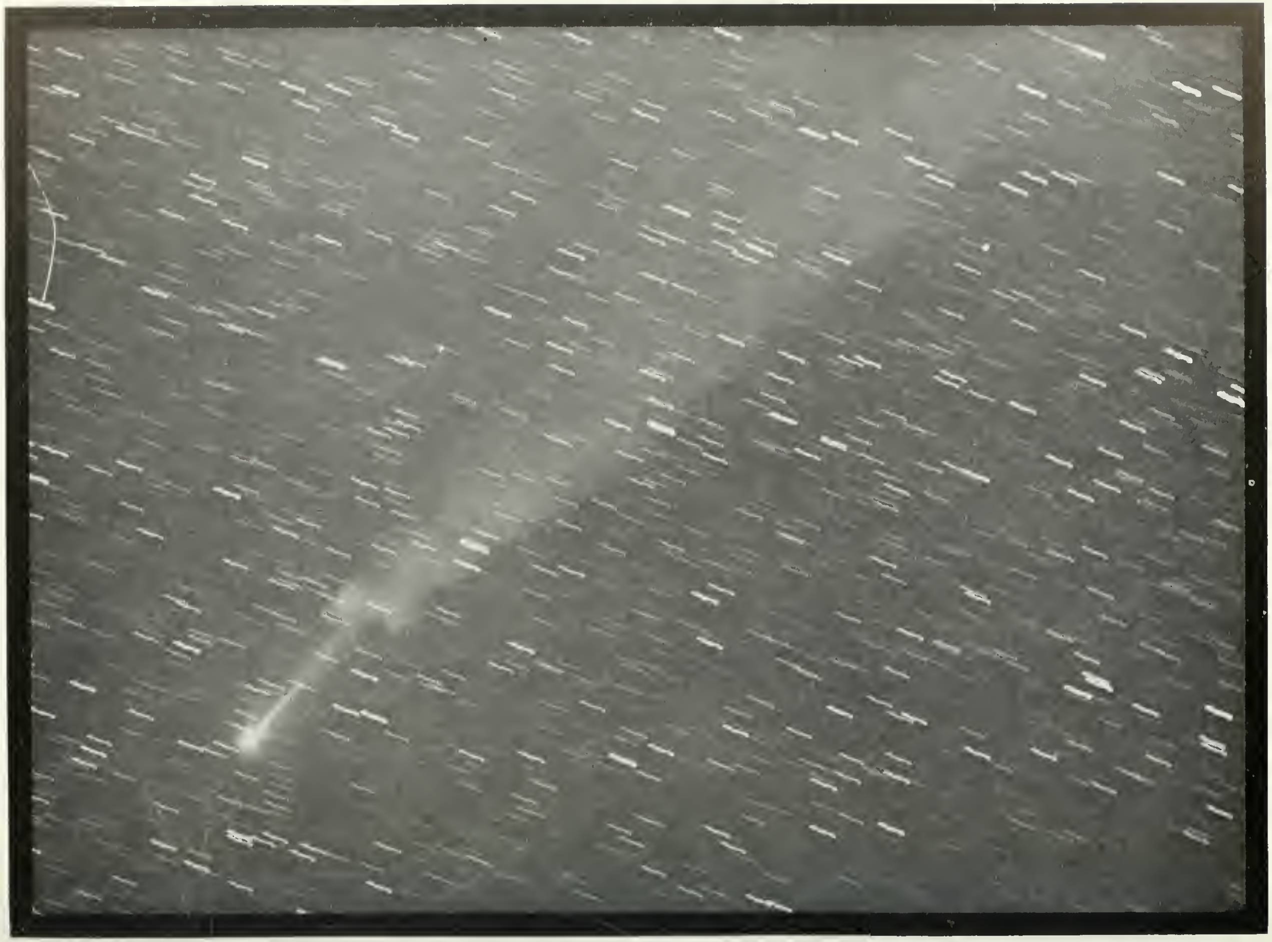
PLATE XXXI

South

COMET 1908 *c* (MOREHOUSE) ON OCTOBER 14, 1908, AT $8^h\ 4^m$ C. S. T. EXPOSURE $1^h\ 10^m$
10-Inch Lens of Bruce Telescope. Scale: 1 cm = 0°.30

PLATE XXXII

South



COMET 1908 *c* (MOREHOUSE) ON OCTOBER 15, 1908, AT 8^h 31^m C. S. T. EXPOSURE 1^h 30^m
10-Inch Lens of Bruce Telescope. Scale: 1 cm = $0\overset{\circ}{.}30$

PLATE XXXIII

South

COMET 1908 *c* (MOREHOUSE) ON OCTOBER 16, 1908, AT $9^h\ 32^m$ C. S. T. EXPOSURE $2^h\ 15^m$
10-Inch Lens of Bruce Telescope. Scale: 1 cm = $0\overset{\circ}{.}30$

then perpendicular to the narrow tail—having shifted through 30° or 40° of position-angle. The different photographs of the 15th show that these masses were receding at the rate of 3′.3 per hour. On the photograph at $6^h\ 58^m$ (Central Standard Time) the distance from the head to the nearest part of the masses was 34′. On the picture at $13^h\ 11^m$ this had increased to 55′. There is no trouble in identifying the masses on the picture of the 16th, though much changed and diffused. On the photograph of this last date at $6^h\ 54^m$ the distance was 113′. At $9^h\ 32^m$ it was 122′. On the plates of the 17th the masses, in a greatly altered form, are still visible, but it is not possible to say which is the main portion of them, for at a distance of 166′ from the head the tail swells out, and at about 218′ this swelling becomes a lump. Neither position will fit well into the motion derived from the plates of the 15th and 16th, but the mean of these distances will agree closely with the earlier motion. It cannot be questioned, however, that it is the same matter that was discharged from the comet on the 15th.

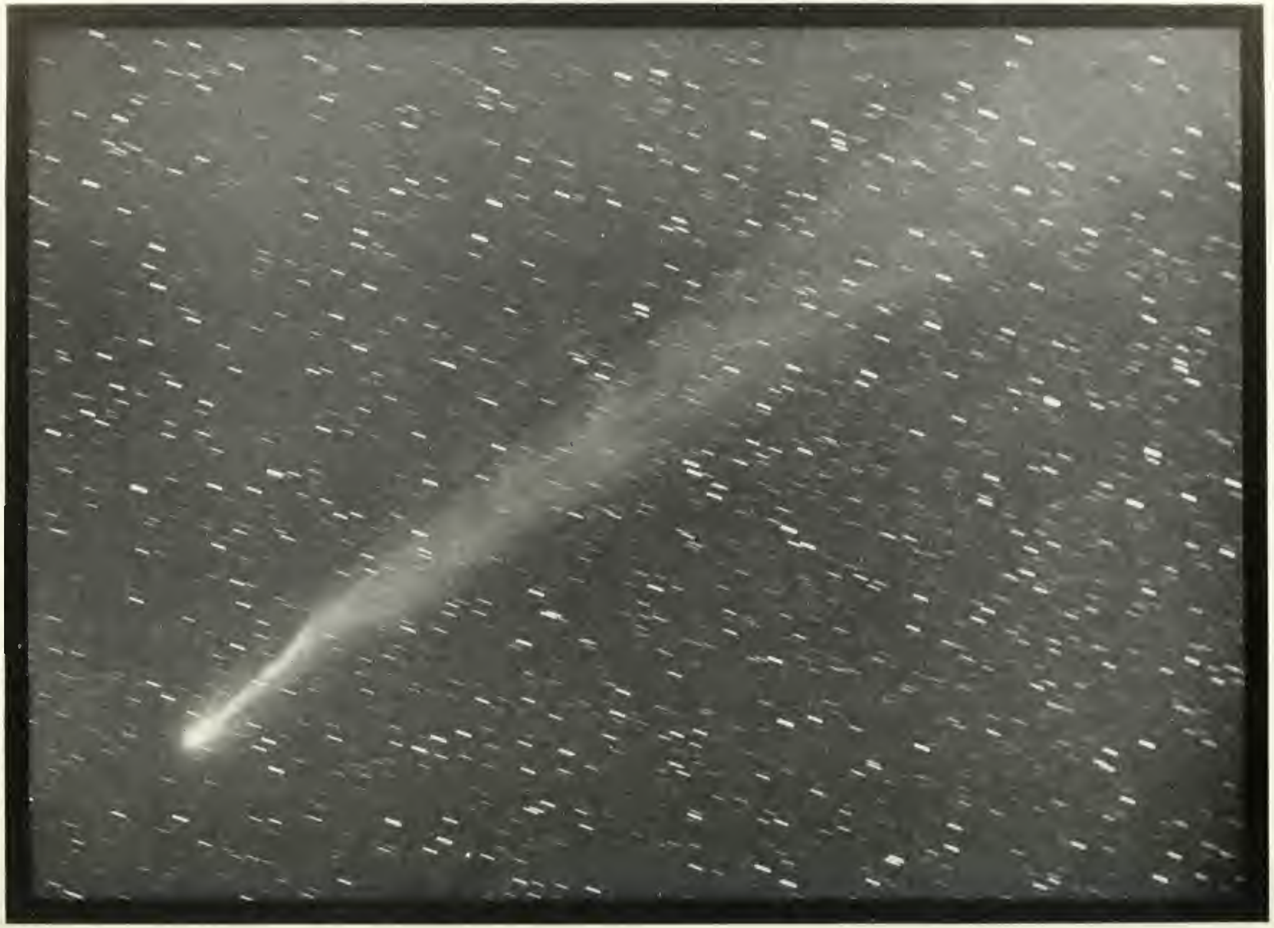
The various photographs of the 15th agree closely in giving an apparent motion of recession of 3½′ per hour. The same value is derived from the two pictures on the 16th. A comparison of the photographs of the 15th and 16th give 3′.30 for the hourly recession in the interval. It would appear from this that there was no acceleration of the motion of these outgoing masses. The individual values for the two dates show that it was uniform. The above value is a minimum because the rear part of the masses was taken in each case. From this motion it is clear that these masses were thrown off from the comet at about 9 A. M. of the 15th, or about 3 P. M. of Greenwich time. Photographs of the comet, therefore, made in the early evening of the 15th in England or on the continent ought to show the masses quite close to the head of the comet. In this picture the tail is full of interesting and peculiar details that cannot be reproduced in the halftone. The impression given by these is that the outgoing matter has been ejected intermittently from the comet, in puffs or pulsations. That there are pulsations in comparatively short periods, in the light of this comet, and undoubtedly in that of others, has been forced upon me while guiding. I first noticed this peculiarity in Daniel's comet (1907 *d*). In the regular micrometric or other observations of a comet, one is not looking at it continuously and hence any change, unless very great, would probably not be seen, but in photographing a comet one's eye is fixed on it for an hour or more and any decided change in brightness will be noticed. In guiding on Daniel's comet last year the impression was persistently given me that the comet pulsated in its light at irregular intervals. At first I took this appearance to be due to fatigue of the eye but I finally concluded that it was really a change in the comet's brightness. I have noticed this same peculiarity in Morehouse's comet. The head would seem to brighten up for a short interval and then become faint again. At these times the head seemed to swell perceptibly. The photographs have shown irregularities in the tail that can perhaps best be explained by a pulsating emission of the matter forming the tail. This is specially noticeable in, among others, the photographs of November 11, where the tail is made up of wavy irregular masses that seem to have been expelled from the comet spasmodically.

An inspection of the photographs of this comet impresses one with the fact that the comet itself is very active in the formation of its own tail: that is, that it ejects the matter with forces within itself, which forces, undoubtedly, are set to work by the disturbing action of the sun. In the *Astrophysical Journal* (**22**, 249–255, 1905) I have given reasons to show that this must be a fact and that the comet itself is more responsible for the production and peculiarities of its tail than the generally accepted theories would indicate.

Another fact shown in the photographs of the present comet is that, though relatively faint visually, it is photographically a bright object, fully as bright as Daniel's comet, if not really brighter. Another proof of this peculiarity is the fact that I have been able to photograph it in strong moonlight and to get a good picture of it showing the tail six or eight or nine degrees long. Its light would seem to be relatively more actinic than the moonlit sky. Under similar conditions it was impossible to get much of a picture of Daniel's comet before the moonlight fogged the plate. On November 5 with the moon 10½ days old nothing could be seen of the tail in the guiding telescope—though the head was quite distinct. Yet an exposure of 50 minutes gave a fine negative showing the tail for 8° or 9°. The usual moonlight fogging occurred of course, but the plate seemed to pick the comet

PLATE XXXIV

South



COMET 1908 *c* (MOREHOUSE) ON OCTOBER 30, 1908, AT $8^h\ 32^m$ C. S. T. EXPOSURE $0^h\ 55^m$
10-Inch Lens of Bruce Telescope. Scale: 1 cm = $0^{\circ}.30$

out from this illumination, and the image is quite strong on this background, and many fine details are shown. It is true the night was very clear and there was, therefore, the minimum sky illumination that the moon's age would allow.

While in several cases the outgoing masses could be followed for two or three days, their forms and details were utterly changed. It was only possible to say that it was the same mass of matter but it was in no sense the same object so far as form was concerned. It will be a great pity if photographs were not made in Europe to give a complete history of the transformation of some of these masses throughout their visible existence.

I have selected the four photographs that accompany this paper because they are among the most interesting, and for the fact that three of the dates, October 14, 15, and 16, cover a most remarkable period of activity in the comet. There is perhaps a suggestion of this great change in the photograph of the 14th on which the comet certainly gives indications of activity. The expulsion of the masses must, however, have really occurred some twelve hours after my last photograph on that night.

The photograph of October 30 is very beautiful and striking in the original. The first part of the tail for about ½° is strong and narrow and seems to be made up of bright twisted forms. It slowly widens until it becomes a great, broad tail 6° or 8° long and convex on its south side.

From a bright portion on the south side, about 40′ from the head, two narrow streamers run tangent to the south edge of the tail for about 2°. From the head, on the south side of the tail, four fine threadlike rays—forming a narrow fan—stream back about ½°. On the north side a broader diffused ray similarly runs back for about ½°.

Though it has not been a conspicuous object, the comet has been above naked-eye visibility for upward of a month. A remarkable brightening occurred on October 27, at which time it was quite noticeable to the naked eye. Its position in the Milky Way has diminished much its chances of becoming a conspicuous object.

In the present table the exposures with the three instruments (the 10-inch, the 6-inch, and the 3.4-inch) were simultaneous. On

LIST OF NEGATIVES OF THE COMET

(Continued from the November Number)

Central Standard Time 1908	Middle of Exposure	Duration	Central Standard Time 1908	Middle of Exposure	Duration
Oct. 26	8^{h} 22^{m}	0^{h} 38^{m}	Nov. 2	7^{h} 32^{m}	0^{h} 55^{m}
28	6 40	1 1	3	7 17	0 49
28	7 55	1 0	4	6 13	0 49
28	9 10	1 0	4	7 9	0 30
28	10 30	0 51	5	6 13	0 53
29	6 20	0 32	5	7 5	0 30
29	8 20	1 0	6	6 39	1 29
29	9 28	1 4	7	6 4	0 49
29	10 35	0 30	8	6 15	0 36
30	6 49	1 2	8	7 23	0 50
30	8 32	0 55	9	6 48	0 33
30	9 55	1 10	10	6 27	1 0±
31	6 9	0 32	10	7 25	0 20
Nov. 1	7 8	0 43	11	6 17	0 50
1	8 40	0 44	11	7 0±	0 13±
2	6 18	1 1			

October 29 at 10^{h} 35^{m} no plate was exposed with the 3.4-inch lens. The last exposure on November 11 was fragmentary through clouds. On the last few dates only broken exposures were obtained through clouds. Though some of these last are not very good, still they give an idea as to the appearance of the tail.

YERKES OBSERVATORY
November 13, 1908

THE RELATIVE INTENSITIES OF THE CALCIUM LINES H, K, AND λ 4227 IN THE ELECTRIC FURNACE[1]

By ARTHUR S. KING

A number of investigations have dealt with the changes in relative intensity of the blue and violet lines of calcium according to the manner of producing the spectrum. Interest has centered about the behavior of λ 3969 and λ 3934 (H and K in the solar spectrum) as compared to that of λ 4227 (*g* in the solar spectrum); the appearance of these lines having been noted by a number of observers in the flame, arc, and spark and by the writer in the electric furnace. Some photographs obtained with the large electric furnace in this laboratory have furnished additional data regarding the dependence of these lines on the physical conditions in the light-source. These results will now be given, with an attempt to summarize the present condition of our knowledge based on the action of the lines in various light-sources.

The line λ 4227 has always been recognized as a "flame line" appearing easily in the flame and in all laboratory sources where a considerable amount of calcium is present. It was shown by Sir William and Lady Huggins[2] that when a very minute trace of calcium is present on platinum or iron terminals in the electric spark the line λ 4227 does not appear (for photographic exposures of ordinary length), while H and K are yet distinctly visible. The other extreme is found in the low-temperature flames, where λ 4227 alone is visible and may be obtained very strong if a large amount of calcium is supplied to the flame. In the oxyhydrogen and other very hot flames the H and K lines appear in the core of the flame, but are weak in comparison to λ 4227 and become weaker as we pass away from the central portion, the outermost part of the flame giving λ 4227 alone. The electric arc gives a similar gradation with higher temperature conditions, the arc at moderate current giving H and K much stronger than λ 4227 in the core of the arc, the relative intensity changing as

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 32.

[2] *Astrophysical Journal*, 6, 77, 1897.

we go outward until in the "flame" of the arc λ 4227 is much the stronger, although H and K are still distinct. The electric spark with self-induction, being near the arc conditions, shows λ 4227 stronger than H and K; while in the highly condensed spark the latter lines are much the more intense. In all these cases a plentiful supply of calcium is assumed to be present.

The amount of calcium vapor in the light-source has considerable influence, λ 4227 in the arc becoming wide or narrow as the supply of calcium is greater or less much more rapidly than do H and K; while in the spark the experiment of Huggins was gradually to diminish the amount of calcium on the electrodes until H and K alone remained. This effect is complicated in the arc and spark, however, by the change in discharge conditions given by varying the amount of metallic vapor.

The effects thus far reviewed indicate that the intensities of H and K are governed largely by the temperature of the source, the condensed spark being assumed to give a condition equivalent to that of very high temperature. A comparison of the flame spectrum of calcium with the electric-furnace spectrum obtained by the writer in a former investigation [1] indicated, however, that other conditions in the flame may especially favor the H and K lines and exert more or less influence on their production in the arc and spark Metallic calcium was vaporized in a graphite resistance tube in an atmosphere of pure hydrogen. The H and K lines did not appear, though most of the prominent calcium lines were present. H and K appeared, however, from traces of calcium salts occurring as impurities when other substances were vaporized in the tube.

The temperature of this furnace was not measured, but there is little doubt that it was as high as that of some of the flames in which H and K are given strongly. This pointed to the conclusion that not only the temperature but the chemical processes of the flame are concerned in the production of these lines. Evidence along the same line is given by a recent work of Hemsalech and de Watteville,[2] in which they found that with the electric method of volatilization H and K were extremely faint in the flames of air with coal-gas, also of

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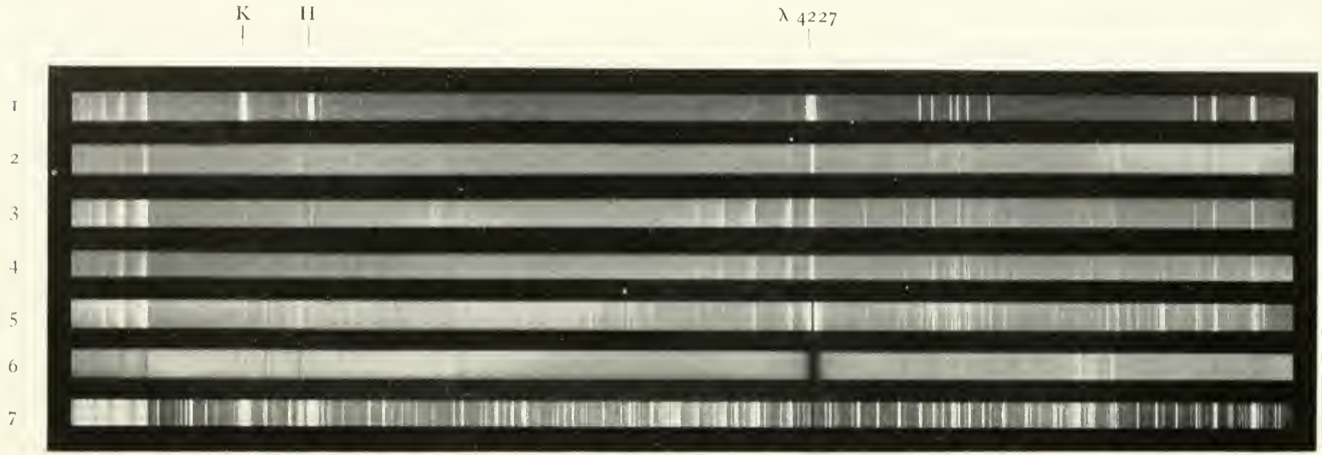
[1] *Astrophysical Journal* **27**, 353, 1908.

[2] *Comptes Rendus*, **147**, 188, 1908.

PLATE XXXV



The Spectrum of Calcium in the Arc and in the Electric Furnace, Showing the Effects of Changing the Temperature and the Quantity of Vapor air with hydrogen, but as soon as oxygen was substituted for air these became the strongest lines of the spectrum with the exception of λ 4227.

Passing to the results obtained with the new electric furnace in the Pasadena laboratory, described in a previous paper,[1] Plate XXXV shows a series of calcium spectra given by the furnace under various conditions. These were photographed with the large Littrow spectrograph,[2] using the first order of a plane grating 5 inches (13 cm) long, with 14,438 lines to the inch (567 lines to the mm). The furnace was operated in vacuum. The resistance tubes were of Acheson graphite of ½ inch (12 mm) inside diameter, and the alternating current was usually used at 20 and 30 volts. The experiments were made before a Wanner pyrometer was added to the laboratory equipment, and as this lot of graphite tubes was exhausted before the temperature measurements began, only estimates based on temperatures measured in other tubes and on the appearance of the spectra can be given, these tubes being of higher resistance than those for which measurements were given in the previous paper. As nearly as can be judged, the furnace at 20 volts gave 2400° to 2500° C., and at 30 volts about 2900° C. The main purpose of this paper is to show the effect of *change* of temperature when different quantities of calcium vapor were present and the temperature intervals given by 20 and 30 volts were large enough to leave no doubt of this effect.

Plate XXXV reproduces (1) the spectrum of calcium in the carbon arc; (2), (3), and (4) are spectra given by a small quantity of calcium in the furnace at different temperatures. Two or three small fragments of clean metallic calcium, weighing together about 0.05 gram, were placed in the graphite tube. Current was available at 5, 10, 20, and 30 volts from the 50 K. W. transformer. As was to be expected, λ 4227 was easily obtained, but a high temperature was required to bring out H and K, probably higher than was attained by the writer's former experiments with the furnace in hydrogen when H and K did not appear. Photograph No. 2 shows H and K barely visible and was obtained in a somewhat indirect manner.

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 28; *Astrophysical Journal*, **28**, 300, 1908.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 27; *Astrophysical Journal*, **28**, 244, 1908.

The furnace had been used for a series of photographs at 20 and 30 volts lasting some ten minutes, with the result that the tube and jacketing were very hot. Ten volts were then put on the tube and No. 2 taken in ten minutes, where one-half to two minutes had been sufficient for strong photographs at the higher voltages. This spectrum should be compared with No. 3, which is an excellent photograph taken with 20 volts on the tube and a temperature that can be safely estimated as 100° to 200° higher than No. 2. This gives the stage when H and K first appear distinctly. It will be noted that λ 4227 is fairly narrow and of nearly the same intensity in these two photographs, while a great change has taken place in the strength of H and K.

A third stage in temperature, still with a relatively small amount of calcium vapor present, is represented by No. 4, made with the furnace at 30 volts. The negative was somewhat lacking in density, but the character of the lines is distinct. H and K appear as moderately strong bright lines with a short exposure. Their width is a little greater than in No. 3. λ 4227 is slightly broadened, with a very narrow reversal (not shown in the reproduction). Other photographs taken at the 30-volt temperature were less favorable for reproduction on account of a continuous ground which masked the H and K lines to some extent. This was due presumably to light from the intensely bright walls of the tube being reflected by the particles of vapor. All direct light from the walls was excluded by the method of focusing the interior of the tube on the slit, leaving out the bright image of the walls. The width of H and K and the reversal of λ 4227 were practically unchanged, however, although in one photograph the continuous ground was strong enough to give all of these as absorption lines. A reversed line in the furnace spectrum means that the cooler vapor near the ends of the tube is emitting with sufficient strength to give a narrow absorption line through the broader emission line given by the vapor in the hottest part of the tube. The occurrence of true absorption lines would then result when the suspended particles reflected enough light from the incandescent walls, in addition to the continuous spectrum given by the particles themselves as white-hot bodies, to give a background for the entire discontinuous emission of the vapor, thus producing dark lines.

Nos. 5 and 6 were taken with the furnace at approximately the same temperature as Nos. 3 and 4 respectively, but with two to three grams of calcium metal in the tube. Therefore some fifty times as much vapor was present as for Nos. 3 and 4. Comparing No. 5 with No. 3, we find H and K slightly broader with more vapor present, but no sign of reversal, thus showing that only the vapor in the middle portion of the tube is hot enough to give these lines. The condition with λ 4227 is very different. It appears as a broadly reversed line, the dark portion being of about the same width as the whole bright line of No. 3, showing that the vapor near the ends is both hot and dense enough to emit (and therefore absorb) strongly, while the large amount of calcium present causes the vapor in the hottest portion to emit a very broad bright line.

Spectrum No. 6 was taken with 30 volts on the furnace and a large supply of calcium in the tube. A comparison with No. 4, taken at about the same temperature, shows the effect of the increased amount of vapor. In the first place, the continuous ground is now strong enough to give all of the metallic lines in absorption. H and K are still to be rated as narrow lines. It is difficult to say how closely their emission is confined to the hottest portion of the tube; but at any rate the large amount of vapor at this temperature is not sufficient to give any decided broadening for these lines. It is λ 4227 which shows an enormous sensitiveness to the increased amount of vapor. The width of the whole absorption line must now be compared with the width of the whole emission line of No. 5, not with the width of the reversal in No. 5. The width of λ 4227 is thus seen to be only slightly greater in No. 6 than in No. 5; the difference being very nearly the same as for Nos. 3 and 4, which had about the same temperature interval with less vapor present. The slightly increased width in Nos. 4 and 6 as compared to their companion photographs may easily result from the increased vaporization in the tube at the higher temperature.

Photograph No. 7 is not a true furnace spectrum, but it throws additional light on the furnace results and besides was taken under conditions so unusual that it is valuable in itself as presenting a distinct condition of the calcium spectrum. The furnace tube, having been operated for some time at 20 and 30 volts with a strong vaporization of the carbon, wore thin and burnt through near its middle. An arc then formed at the break, a heavy current passing at 30 volts, as the large area of the ends combined with the presence of calcium vapor sufficed to maintain the arc at the low voltage. An exposure of 15 seconds then gave photograph No. 7. We thus have a spectrum given by the light from a high-current arc at low voltage passing through some five inches of calcium vapor heated probably well above 2500° C. There is considerable continuous ground, but H and K show as broad, bright lines, much wider than in No. 1 (given by calcium chloride in the ordinary carbon arc) and enormously stronger than in any of the furnace spectra. The fact that there is no dark line through the center indicates that the cooler vapor at the ends of the tube does not emit these lines with any appreciable strength. This end vapor may have suffered a considerable fall in temperature owing to the voltage being now largely concentrated at the arc. λ 4227 is a dark line of about the width of the reversal in No. 5, but without the wide emission line on which the dark line in No. 5 is superposed. The negative shows bright edges to the absorption line, but the arc formed by the broken tube evidently does not give λ 4227 with much intensity. We have here, in fact, very strong arc conditions, as indicated by the strength of H and K compared to λ 4227: conditions similar to those given by the core of a heavy current arc in air, and more pronounced than those of the arc at moderate current shown in No. 1.

The calcium spectrum as far as the series triplet λ 4426–λ 4456 is reproduced in Plate XXXV. Numerous relative differences among the calcium lines may be seen at different furnace temperatures and between furnace and arc, notably in the group λ 4283–λ 4319. These will be considered in a later paper in connection with other regions of the calcium spectrum.

DISCUSSION

The furnace results show very distinctly the conditions governing the intensity of λ 4227. It appears at a low temperature, and is not strengthened in proportion as the temperature rises. It is, however, very sensitive to changes in the amount of luminous vapor and may be enormously strengthened even at moderate temperatures by a large supply of calcium. A comparison of photographs Nos. 3 and 5, taken at approximately the same temperature, brings out this relation very clearly. The readiness of the line to reverse in the arc is due to the strength with which the cooler outer layers of the arc radiate this line and therefore absorb the light from the hotter region of the core. The conditions for reversal are still more favorable in the furnace on account of the length of the radiating column, the cooler ends of which give strong absorption.

The production of H and K is more complex, but the furnace shows that they may be obtained if the temperature is sufficiently high (close to 2500° C.) without the aid of chemical action, although the latter may aid in their production in sources of lower temperature. They are to be rated as high-temperature lines, by reason both of the temperature required for their production and because their increase of strength in the furnace is closely proportional to the temperature—very much more so than in the case of λ 4227. The furnace gave them always as narrow lines, bright unless the continuous background was strong enough to reverse the whole spectrum. Their refusal to show "self-reversal" in the furnace is in line with the fact that their reversal is usually narrow in the arc: the cooler regions in both sources can emit the lines only weakly if at all. It cannot be said, however, that the amount of vapor has no effect. The lines widened slightly in the furnace with increase of vapor, but the change is small. The intensities of the lines in different electrical sources, as the core and flame of the arc, the spark with and without self-induction, are all in line with the hypothesis that the strength of the H and K lines depends very largely upon the temperature of the source. The results from the furnace work do not explain all of the phenomena shown by H and K in the arc. Their intensity in the arc is so much greater that the conditions for their emission seem to be on a different plane from those prevailing in the furnace, the difference being out of proportion to the probable thermal interval between the two sources.

Applying these conclusions to solar phenomena, the behavior of the lines H, K, and λ 4227 in sun-spot spectra does not throw much light on the physical condition of sun-spots on account of the short wave-length of these lines, this region not showing changes in its lines consistent with those observed in the region of greater wave-length. Thus the fact that λ 4227 shows little change in sun-spots does not justify statements concerning the vapor-density in spots based on this line.

The behavior of the lines in the solar chromosphere is, however, of high interest. Numerous eclipse observations have shown that H and K appear alone in the higher regions of prominences, λ 4227 appearing only when the vapor in the chromosphere has reached a considerable density. This is entirely consistent with the conclusions of this paper regarding the conditions favoring these lines.

Mount Wilson Solar Observatory
October 1908

THE SPECTRUM OF *MARS*

By V. M. SLIPHER

The spectrum of *Mars* has been more generally and critically observed than that of any other planet, not on account of a unique spectrum, but because information might in this way be gained of the atmosphere enveloping this interesting object. It was one of the first celestial spectra to be examined and has since been frequently observed by the most skilled observers.[1] All observations previous to 1895 were made visually, and, excepting those made by Campbell,[2] at Lick Observatory, in 1894, all concurred in indicating for *Mars* an atmosphere similar to that of the earth. The contradictory observations of Campbell led Sir William and Lady Huggins[3] and the late Professor Vogel[4] to renew, in 1894, their earlier observations, with the result that they were again satisfied that the spectrum of *Mars* showed evidence of absorption due to its own atmosphere. However, Campbell worked under favorable conditions and his results and the conclusions of Jewell[5] disturbed the confidence felt in the earlier observations, as Vogel evidently realized in 1895, when he wrote in his review article on planetary spectra, "I believe it will be necessary to wait for still further observations, perhaps also those made from another point of view, before the question can be definitely settled."

The difficulties in the way of a successful solution of the problem by the methods then employed were brought out in the discussions[6] which at this time naturally followed. Chief among these was the impossibility of having alongside that of *Mars* a suitable comparison spectrum to enable the two to be simultaneously and repeatedly

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[1] Rutherfurd, *Am. Jour. Sci.*, **35**, 71, 1863; Huggins, *Monthly Notices*, **27**, 178, 1867; Vogel, *Untersuchungen über die Spectra der Planeten*, Leipzig, 1874; Janssen, French Academy of Sciences, July 1895; Maunder, *Monthly Notices*, **38**, 34, 1877.

[2] *Pub. A. S. P.*, **6**, 228, 1894, and *Astronomy and Astrophysics*, **13**, 752, 1894.

[3] *Astrophysical Journal*, **1**, 193, 1895.

[4] *Ibid.*, **1**, 203, 1895.

[5] *Ibid.*, **1**, 311, 1895.

[6] *Ibid.*, **2**, 28, 1895; **1**, 311, and **3**, 255, 1896.

compared and studied. With the methods then used the best that could be done was to observe *Mars's* spectrum and then turn the telescope on the moon whose altitude was not greater than that of the planet, and to compare the mental image of the spectrum of the one with the spectrum of the other. But the more or less dissimilar conditions prevailing for the two objects and the carrying of the mental image over through some period of time, must have introduced a serious factor of uncertainty.

That the application of photography to the problem would eliminate many difficulties was now realized. However, hope of success required that the less refrangible spectrum be photographed, and the plates of this epoch were very poor for such purpose. Nevertheless Campbell,[1] in 1895, and Keeler,[2] in 1897, applied the plate, only to obtain negative and noncommittal results. More efficient plates had to be awaited. By 1905[3] somewhat better ones were available, and the problem was then tried here by a different method, but the results were still indecisive. The recent great improvement of plates for the yellow, orange, and red spectrum encouraged another attempt and promised a definite solution of the problem.

The elevation of this observatory, 7250 feet (2210 meters) above sea-level, gives it advantages for planetary spectroscopy not enjoyed by any other similarly equipped observatory. At Flagstaff the barometric pressure is only three-fourths of that at sea-level, and as the location is far inland and wholly surrounded by desert or semi-desert country, the air is very dry and the conditions are peculiarly favorable to the delicate study of the spectrum of *Mars* for atmospheric absorption, particularly that due to water-vapor. In general the gases of the air are distributed according to the laws of gaseous diffusion and their power of absorption decreases with the barometric pressure. Here, with a pressure of twenty-three inches, the spectrum of oxygen, for example, would have three-fourths its strength at sea-level. But the distribution in altitude of the vapor of water is quite

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[1] *Ibid.*, **5**, 235, 1897.

[2] *Ibid.*, **5**, 328, 1897.

[3] *Lowell Observatory Bulletin*, No. 17. See also "Spectrum of *Jupiter*," by Millochau, in *Bulletin astronomique de France*, November 1904, and "The Spectrum of *Mars*," by Marchand, *loc. cit.*, July 1905.

different, aside from varying in amount between wide limits depending upon meteorological conditions. Its decrease with increase of altitude is readily apparent from the following table, copied from Cleveland Abbe's treatise on "Meteorology" in the *Encyclopaedia Britannica*, 10th ed., Vol. XXX, p. 696:

TABLE I

Altitude in Feet	Relative Tension e/e_0	Amounts of Vapor at Different Temperatures Expressed in—							
		Grains per Cubic Foot				Inches of Rainfall			
		80°	70°	60°	50°	80°	70°	60°	50°
0	1.000	10.95	7.99	5.76	4.09	0.0	0.0	0.0	0.0
6,000	0.524	5.75	4.19	3.02	2.14	1.3	1.0	0.7	0.5
12,000	0.275	3.01	2.20	1.58	1.12	2.1	1.5	1.1	0.8
18,000	0.144	1.58	1.15	0.83	0.59	2.5	1.8	1.3	0.9
24,000	0.075	0.82	0.62	0.43	0.31	2.7	2.0	1.4	1.0
30,000	0.040	0.43	0.32	0.23	0.16	2.8	2.1	1.5	1.1

These data show that the elevation of this observatory brings it above fully half of the moisture of the air. From this table it will also be observed that the air's capacity for moisture is less the lower the temperature. Unfortunately, during its near approach in 1907, *Mars* was low in the south and brightest in the summer months when the earth's atmosphere possessed its maximum capacity for water. The observations of its spectrum were therefore postponed until the winter months, when the planet's northern declination would place it much higher in the sky, and when our air contained a minimum of moisture. The importance of observing at a low temperature cannot be overestimated. These two conditions were essential and quite outweighed the loss of light attendant upon the recession of the planet meanwhile, the only disadvantage being the prolongation of the exposures which somewhat limited the accumulation of plates.

The character of the groups of lines and bands in the spectrum of the earth's atmosphere and in planetary spectra generally led me to use a single-prism spectrograph as being the one best suited to the problem under the prevailing conditions. The series of exposures were made with this low-dispersion instrument attached to the 24-inch refractor.

The sensitive plates employed were Seed "23" which I sensitized to the lower spectrum by bathing them for three or four minutes in a bath made up as follows:

Water	8	ounces
Dicyanin	45	minims
Pinaverdol	75	"
Pinacyanol	28	"
Ammonia	120	"

Upon removal from this bath the plates were washed in water or rinsed in alcohol and dried in a warm current of air from an electric fan. This combination of dyes is the best one among a number which I made up and experimented with about a year since. It gives a plate whose sensitiveness to the prismatic solar spectrum, with normal exposure, is fairly uniform down to λ 7000 where it begins to weaken and is just sufficient in the region about A to record this line.

The great value of this plate for the present research lay in the region of the spectrum it makes accessible for study. Almost all the dark lines observed in the solar spectrum below C originate in the earth's atmosphere, and, too, the most prominent of the telluric lines and bands are found below this line. Hence the importance of a study of the spectrum of *Mars* below C where it is unmasked by solar lines will be apparent, and all the more so since, owing to the less sensitiveness of the human eye to these longer wave-lengths, the earlier observers could not include this region in their study of the spectrum. The range of sensitiveness of this plate includes the *a* band which is located midway between the oxygen bands A and B. This double band is due to the absorption of water-vapor in the air and is much the strongest of the water-vapor groups of lines, as a glance at the two images of the solar-terrestrial spectrum will show. Previous observations for evidence of aqueous vapor in *Mars* were of necessity confined chiefly to the rain-band in the region about and below the D lines. But as this band, masked as it is by heavy solar absorption, is visible only when the light has traversed a large amount of moisture in our air, it is not suited for such delicate observations, as was pointed out by Jewell. On the other hand, the *a* band is visible when the moisture in the light-path is very inconsiderable. It is conspicuous when the rain-band is not to be seen, which is brought out clearly in the two images of the solar-terrestrial spectrum. However, in cold dry winter weather, at Flagstaff, this band is all but invisible, and is, therefore, well suited for the problem in hand. While an extremely sensitive test under these conditions, observations of it in comparative spectra of the sun and *Venus*, near the zenith, made during our dry weather in June show that the *Mars* observations could hardly have succeeded had they been attempted in the summer.

A cylindric lens placed before the slit of the spectrograph gave the spectrum a width of 1.4 millimeters and an even intensity throughout. The comparison spectrum of the moon was made the same width and was timed to equal that of *Mars* in intensity as well. This extreme breadth of the spectra facilitated the detection of slight differences between them which would otherwise have been invisible.

In Table II is a list of the plates with the data appertaining.

TABLE II

Plate No.	Date 1908	Altitude		Air Column	Vapor per Cubic Foot
		Mars	Moon		
Rm 3039...........	January 10	48°	48°	1.35	0.74 grains
Rm 3050...........	January 15	43	30*	1.47	1.30*
Rm 3054...........	January 16	46	46	1.39	0.95
Rm 3061...........	January 20	44	42	1.44	1.01
Rm 3062...........	January 21	41	41	1.52	1.02
Rm 3076...........	February 14	40	40	1.56	0.62
Rm 3080...........	February 17	37	(38)	1.66	0.70
Rm 3081...........	February 18	38	38	1.62	0.50

* A long series of exposures to the spectrum of the moon at different altitudes, made on this same night, interfered with getting this comparison before the moon was somewhat lower than was *Mars*. They verify the lunar images of the *Mars* spectrogram in showing that the moisture in our air was relatively very much less than for plate Rm 3062, notwithstanding the meteorological records to the contrary. The strength of the *a* band depends upon the actual amount of aqueous vapor in the light-path and is, therefore, a very reliable measure, whereas the meteorological observations cannot be reliable for they depend upon the moisture in a small sample of air at the earth's surface which may be very different from what it is a short distance above. A spectrogram of the sun would show by the strength of the *a* band as compared with a scale the total amount of vapor in the air column and there is no good reason why this method should not now displace the present one.

In the several columns of this table are to be found the plate number, the date, the altitude of *Mars* and the moon as computed[1] for the middle of the exposure of each, the length of the light-path in the air in terms of the vertical, and the water-vapor in grains

[1] The altitude of *Mars* was computed for the middle of the exposure, then the hour-angle of the moon computed for that altitude and the exposure made accordingly.

per cubic foot of air, extracted from the official records of the Flagstaff station[1] of the U. S. Weather Bureau. If the mean of the last column, 0.85 grains, be multiplied by the average length of air column 1.5, we get 1.27 grains, which, as will be seen from Table I, corresponds to an elevation of eleven thousand feet if the air temperature be 50° F. Thus these plates were photographed through only about one-fifth as much vapor as would have been encountered by an observer working at sea-level at the same temperature and with the planet at the same altitude. Hence as concerns tests for water-vapor on *Mars* we are justified in stating that this series of plates was made under meteorological conditions which were extremely favorable.

The results of an examination of the individual plates with particular regard to the *a* band[2] will now be given. Unless otherwise stated each plate contains one image of the spectrum of *Mars* and two of the moon, those of the latter differing a little in exposure to facilitate comparison.

Rm 3039. The spectra are well matched in density. The *a* band is stronger in *Mars* than in the moon. Elsewhere no differences between the spectra are found.

Rm 3050. The image of *Mars* is somewhat stronger than those of the moon, but this is a very good plate. The *a* band is all but invisible in both lunar images, but conspicuous in *Mars*. A band a little more than half-way from *a* to B may be a trifle stronger in *Mars*, otherwise the spectra are alike.

Rm 3054. The spectra are well matched in density. Band *a* may be slightly stronger in *Mars*, but the difference is too small to warrant a definite statement.

Rm 3061. No certain differences were found between the spectra of this plate, but band *a* is quite strong in both.

Rm 3062. This is one of the best plates of the series. The *a* band, although strong in both, is stronger in *Mars*. There may be more absorption in *Mars* between *a* and B than in the moon, but this is not certain.

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[1] This station is located in the valley, a little more than a half-mile distant, and about 350 feet below the Observatory.

[2] Although this is here called the *a* band, it is however to be understood to refer to the less refrangible and stronger component of the double band commonly denoted by *a*.

Rm 3076. *Mars's* spectrum is somewhat weak, and as the film is slightly defective over the red end of the spectra, the plate will not be further considered.

Rm 3080 and 3081. As the lunar spectrum failed on plate 3080, these two plates, made on consecutive nights and under settled meteorological conditions, were fastened together film to film for examination, so as to have an image of the lunar spectrum of 3081 appear between the two spectra of *Mars*. The band *a* is distinctly reinforced in both the *Mars* plates. No other differences between these spectra are apparent.

It should be remarked that these plates show the continuous spectrum of *Mars* to be brighter than that of the moon between λ 5600 and λ 7000, a characteristic of the spectrum which was to be inferred from the planet's red color.

The results of the examination of these plates lead to the conclusion that the *a* band is reinforced in *Mars* due to absorption in its atmosphere. Although some of the plates may be indecisive, the majority assert this and none denies it. In general, those that show little or no difference exhibit by their lunar images strong terrestrial absorption, and those that show a marked difference exhibit weak terrestrial absorption. In other words, the delicate Martian component is easily masked by the terrestrial one and apparently cannot show unless the latter is very weak.

Since this band in the spectrum of the earth's atmosphere has been found to be due to absorption by aqueous vapor and it appears to be identical in the two spectra except for the difference in strength, the reasonable conclusion is that the spectrograph has revealed the presence of water in the atmosphere of *Mars*.

Aside from reinforcement of the *a* band the spectrum of *Mars* shows no selective absorption not found in that of the moon photographed under the same conditions. It might seem that the oxygen bands A and B and *a* should appear of increased strength in the planet, but the conditions were much less favorable to the detection of absorption of this gas than that of water-vapor. Despite our elevation the light of *Mars* and the moon traversed one and one-eighth times as much oxygen as it would have encountered if these objects had been in the zenith and the observations made from sea-level.

Thus the telluric component of the oxygen spectrum would mask the Martian one even if this latter be not weak, since the two would be superposed with the dispersion[1] used. It is true also that the plates of this series are rather dense at B and too weak at A to be well suited to the search for oxygen absorption, and its detection need not be considered impossible.

In Plate XXXVI, Fig. 1 and Fig. 2 show direct enlargements of two plates of *Mars* and the moon and Fig. 3 shows two impressions of the solar-terrestrial spectrum corresponding to high and low sun. Fig. 1 displays well the difference between the spectra when the moisture in the terrestrial air was slight enough to allow the Martian component to reveal itself, while Fig. 2 shows how this difference decreases when the telluric component becomes stronger. In Fig. 1 it will be seen that not only is the head of *a* very strong but the bright "line" between it and the tail is distinctly present. A glance at Fig. 3 will suffice to demonstrate the great advantage of working in the region of the *a* band rather than of the rainband near D.

More observations are needed before any definite statement can be made of the amount of water-vapor in the Martian atmosphere. Obviously these results are compatible with *snow*-caps and a comparatively moderate temperature and stand in direct contradiction to *hoar-frost*-caps and a low temperature for *Mars*.

LOWELL OBSERVATORY
FLAGSTAFF, ARIZONA
June 1908

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[1] The application of velocity-shift, after the manner proposed by Dr. Lowell in *Bulletin* No. 17, promises to be the best test for oxygen absorption. A spectrogram made with a spectrograph giving as great resolution of lines at B as the Lowell three-prism one gives at λ 4400 should show the Martian oxygen lines separated from the terrestrial ones, if the observation is made when *Mars* is near quadrature.

PLATE XXXVI

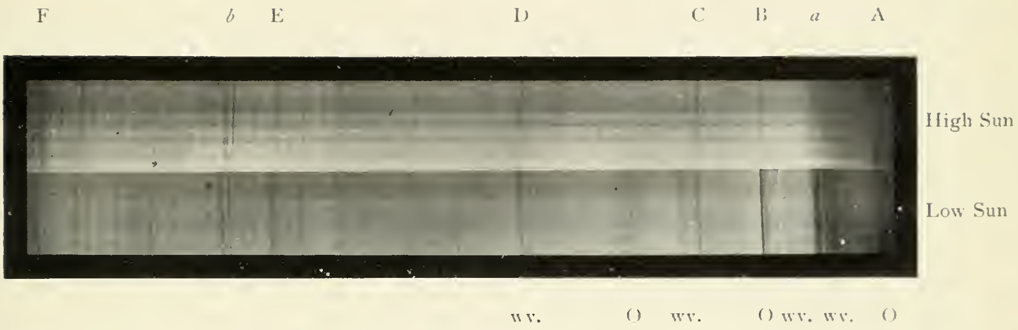

Fig. 3.—Solar-terrestrial Spectrum

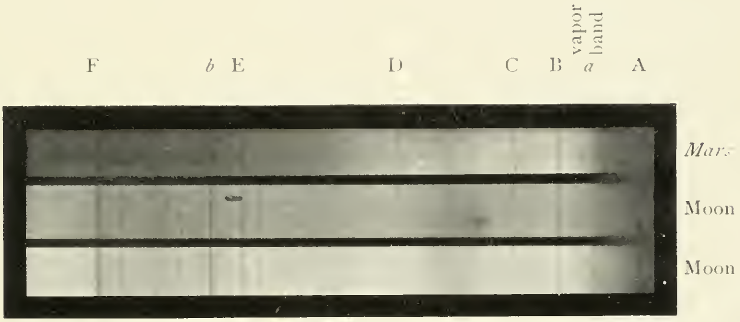

Fig. 2

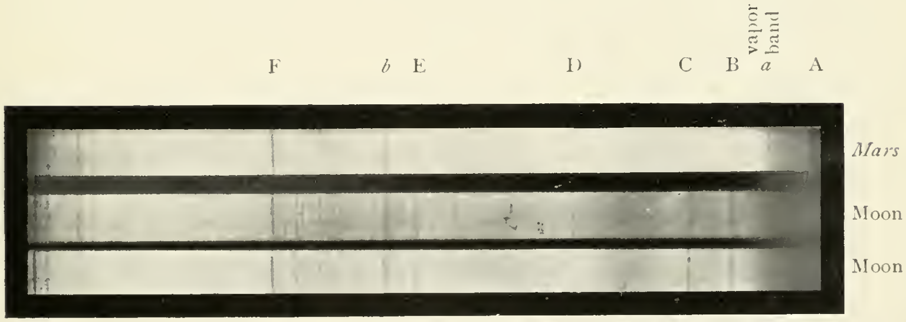

Fig. 1

Spectrograms of *Mars* and Moon

REVIEWS

Handbuch der Spectroscopie. By H. KAYSER. Band IV. Pp. xix+1248; Figs. 137. Leipzig: S. Hirzel, 1908. 72 Marks; bound, 76 Marks.

The fourth volume of Professor Kayser's great work on spectroscopy is by far the most interesting of all. Of its 1200 pages all but the first 250 are devoted to dispersion, phosphorescence, and fluorescence. It seems a pity that the first chapters, which are devoted to the absorption spectra of animal and vegetable coloring matters, could not have been brought out with Vol. III, which is devoted exclusively to absorption spectra, and contains less than six hundred pages in all.

The treatment of dispersion was written by Dr. A. Pflüger, whose valuable contributions to the subject are well known. It is doubtful if this portion of the work could have been put into better hands, for Dr. Pflüger has devoted much time to the experimental verification of dispersion formulae, and is thoroughly familiar with the subject in all its aspects. It is by far the most complete and explicit treatment of the subject that has ever been given. The various theories, mechanical and electromagnetic, are very fully developed, and practically every experimental verification of importance which has ever been made is described in detail. Especial attention is paid to the closely related phenomena of selective absorption and reflection, and many obscure points are cleared up, such as the apparent dependence of the refractive index upon the angle of incidence in the case of strongly absorbing media.

A brief account of the theory of Julius by which many solar phenomena are accounted for by anomalous dispersion is given, and it is to be regretted that the last paper on the subject appeared too late to be included. Three hundred and fifty pages are given in all to dispersion, the whole forming the most complete history of the subject from the historical, experimental, and theoretical side that has ever been written. In spite of the great length of the treatment, the matter is presented in such a way that nearly all of it is extremely readable.

The chapters relating to phosphorescence were written by Professor Kayser. As he says in his introduction, it is impossible to draw a sharp line between fluorescence and phosphorescence. We are accustomed to think of fluorescent substances as emitting their light only during the time of their excitation, while phosphorescent bodies continue to glow after the stimulating radiations have ceased to fall upon them. It is possible, however, to pass by gradual steps from a fluorescent body to a phosphorescent body, as in the case of flourescent dyes embedded in gelatine, or, vice versa, as in the case of a phosphorescent body transformed into a fluorescent one by elevation of temperature.

It is not Professor Kayser's fault that this portion of the book is less interesting than the preceding. We know practically nothing about the mechanism of phosphorescence. While an immense amount of interesting experimental work has been done and many interesting phenomena have been discovered, no theory has been evolved which can be subjected to experimental proof. The presentation of the subject is excellent and it is impossible to read it, even superficially, without deriving many inspirations, for Professor Kayser is always careful to point out lines of work which can be followed up with profit. The chief end of a work of this nature is attained if it compels the reader to think for himself, and if profitable thought is not aroused by this book, it is the misfortune of the reader and not the fault of the author.

The historical treatment of the subject is followed by a very full account of the various types of phosphorescence excited by light, heat, mechanical means, cathode rays, canal rays, and Röntgen radiations. Becquerel's work with the phosphoroscope, and the investigations of Crookes and others on the phosphorescent spectra of the rare earths, the extinguishing action of the infra-red radiations, low-temperature effects, and a host of other phenomena are dealt with in turn, and their bearing upon the various attempts that have been made to explain phosphorescence discussed. In closing, Professor Kayser points out that all of the theories, both mechanical and electrical, are based upon the same supposition that an unstable modification is formed by the action of the light, the reverse process being accompanied by the emission of radiant energy. The portion of the book relating to fluorescence was prepared by Dr. H. Konen, and is fully up to the standard of the rest of the work. Three hundred and fifty pages are devoted to the subject, the treatment closing with a list of nearly two thousand fluorescent substances, with notes on the nature of the light in each case.

The subjects dealt with are as follows: historical survey (50 pages); fluorescent line spectra of iodine, mercury, sodium, and potassium vapors (40 pages); fluorescent band spectra (150 pages), including the absorption of fluorescing substances, the influence of the solvent, temperature, and state of aggregation, the ultra-microscopic investigations of Siedentopf and Zsigmondy, polarized fluorescence of crystals, and other phenomena too numerous to mention. Many promising lines of investigation are suggested, and attention is drawn to doubtful points which require further experimental study.

Upon the whole I am inclined to regard this book as the most interesting which has appeared within recent years, and feel tempted to insert it in the oft-quoted saying that "The student armed with the calculus and the spectroscope cannot fail to discover new and important laws of nature." For my own part, if my library were to be reduced to two works, I think that I should select Kayser's *Handbuch* and Lord Rayleigh's *Collected Papers*.

R. W. Wood

Sir George Gabriel Stokes: Memoir and Scientific Correspondence. Selected and arranged by JOSEPH LARMOR. Cambridge University Press, 1907. 2 vols. Pp. 475 + 507.

In his Baltimore Lectures the late Lord Kelvin said (p. 101):

> But so far as I am aware the very first idea of accounting for absorption by vibrating particles taking up, in their own modes of natural vibration, all the energy of those constituents of mixed light trying to pass through, which have the same periods as those modes, was from Stokes. He taught it to me at a time that I can fix in one way indisputably. I never was at Cambridge but once from about June, 1852, to May, 1865; and it was at Cambridge, walking about in the grounds of the colleges that I learned it from Stokes. Something was published of it from a letter of mine to Helmholtz, which he communicated to Kirchhoff and which was appended by Kirchhoff in his postscript to the English translation (published in *Phil. Mag.*, 1860) of his paper on the subject which appeared in Poggendorff's *Annalen*, Vol. CIX, p. 275.

In another lecture on "The Size of Atoms" Lord Kelvin said:

> Now I want to bring before you something that was taught me a long time ago by Professor Stokes; year after year I have begged him to publish it, but he has not done so, and so I have asked him to allow me to speak of it tonight. It is a dynamical explanation of that wonderful phenomenon called fluorescence or phosphorescence (*Popular Lectures*, Vol. I, p. 204).

The scientific correspondence of the man from whom Kelvin learned the meaning of the Fraunhofer lines and the dynamics of fluorescence is likely to be of more than passing interest to the spectroscopist.

For the purpose of illustrating the easy style of these letters and the innate modesty of their author as well as to illuminate the history of a fundamental theorem in spectroscopy, the following portion of a letter to Sir Henry Roscoe may be quoted:

Cambridge, February 7, 1862

Dear Mr. Roscoe: My share in the history of solar chemistry, I look upon it, is simply *nil;* for I never published anything on the subject, and if a man's conversations with his friends are to enter into the history of a subject, there is pretty nearly an end of attaching any mention or discovery to any individual.

As well as I recollect what passed between Thomson and myself about the lines was something of this nature. I mentioned to him the repetition by Miller of Cambridge of Fraunhofer's observation of the coincidence of the dark line D of the solar spectrum with the bright line D of certain artificial flames, for example a spirit lamp with a salted wick. Miller had used such an extended spectrum that the two lines of D were seen widely apart, with six intermediate lines, and had made the observation with the greatest care, and had found the most perfect coincidence. Thomson remarked that such a coincidence could not be fortuitous and asked me how I accounted for it. I used the mechanical illustration of vibrating strings which I recently published in the *Phil. Mag.* in connection with Foucault's experiment. Knowing that the bright D line was specifically characteristic of soda, and knowing too what an almost infinitesimal amount suffices to give the bright line, I always, I think, connected it with soda. I told Thomson I believed there was vapor of sodium in the sun's atmosphere (Vol. II, p. 83).

When the promised correspondence between Kelvin and Stokes has made its appearance important material may be added to this interesting chapter in the history of science. In the meantime it is important that in our thought we do not minimize the originality of either Kirchhoff or Bunsen.

The fact that Professor Larmor had undertaken to edit this correspondence was an ample guarantee that it would be worthily done.

Those who wish an authoritative, clear, and most entertaining sketch of the life of Sir George Stokes, especially with reference to its social side, will find this in the first fifty pages, which are devoted to biographical notes and recollections by his daughter, Mrs. Laurence Humphrey. This sketch is follpwed by appreciations from various colleagues.

Next come the letters, arranged in certain natural groups, those of each group having been placed nearly in chronological order. Throughout these series of letters are interspersed many editorial remarks which do much to preserve the continuity and interest of the narrative. In one of these notes (p. 149) is detailed Stokes's discovery, in 1853, that the metallic spark has an ultra-violet spectrum several times longer than its visible spectrum. This find, like Helmholtz' invention of the ophthalmoscope, was made in course of preparation for an experimental lecture. In another of these notes is inserted Stokes's vice-presidential address before the British Association for the Advancement of Science in 1862. In these few lines, which occupy less than one octavo page, is a bit of advice which, if heeded, would do much to ameliorate the long sessions of many of our scientific meetings in America. I cannot refrain from quoting:

> It must be remembered that minute details cannot be followed in an exposition *viva voce;* they must be studied at leisure; and the aim of the author should be to present the broad, leading ideas of his research, and the principal conclusions at which he has arrived, clearly and briefly before the section (Vol. I, p. 198).

Those astrophysicists who continue to demand better gratings than the best that have hitherto been ruled and those shopkeepers who have again brought Barton's buttons into vogue may take comfort in the following letter (p. 154) from Sir David Brewster to Stokes, dated 1864:

> I would esteem it a particular favor if you could lend me any specimens of grooved glass which give good diffracted spectra. I possess the very finest specimens upon steel executed by the late Sir John Barton; but I have been stopped in prosecuting a very curious discovery by the imperfections of my specimens of grooved glass.

On p. 218 an editorial comment includes the following valuable characterization of Maxwell and Stokes:

> With Maxwell the scientific imagination was everything: Stokes carried caution to excess. Maxwell revelled in the construction and dissection of mental and material models and images of the activities of the molecules which form the basis of matter: Stokes's published investigations are mainly of the precise and formal kind, guided by the properties and symmetries of matter in bulk, in which the notion of a molecule need hardly enter. Kelvin stands perhaps half way between them. In the main features of his activity he could rightly be described, as he has himself insisted, as a pupil of Stokes; but along with this practical quality there worked a constructive imagination which doubtless, next to Faraday, formed the main inspiration of Maxwell.

The multiphase activity of Stokes is nowhere better represented than in the correspondence which arose from his secretaryship in the Royal Society. To writers on the most diverse subjects he is ever offering helpful suggestions in a tactful manner. As chairman of the Government Committee on Solar Physics he was for many years an efficient leader in that branch of science which we now call astrophysics. His position as the most eminent geodesist of England made him a constant adviser on the work of the Indian Pendulum Survey. As to giving up his time, talents, and energy to these various objects there seems never to have been any hesitation. The marvel is that time was found not only for these by-products, so to speak, but also for five volumes of mathematical and physical papers, not to mention teaching. On pp. 268–69 is to be found Kelvin's excellent and authoritative summary of Stokes's achievements given on the occasion of the latter's receiving the Copley Medal. Combining with this Lord Rayleigh's estimate, on pp. 318–20, one has perhaps the best obtainable brief sketch of Stokes's scientific career. Such a large portion of his work lies outside of his published researches that the correspondence contained in the two volumes under review is really essential to complete the picture.

One of the most charming features of these letters is the marked confidence and freedom with which everyone approaches Stokes, due to the absolute candor, perfect simplicity, profound scholarship, and complete unselfishness of the man.

The publication of the letters which were exchanged between Stokes and Kelvin is awaited with unusual interest.

Henry Crew

COMMITTEE ON COMETS

The Committee of the Astronomical and Astrophysical Society of America has issued the following circular:

Madison, Wis., October 1, 1908

In the belief that our knowledge of comets may be considerably enlarged through a proper use of the opportunities presented by the approaching return of Halley's Comet and the systematic observation of such other cometary phenomena as may be presented during the next few years, the Astronomical and Astrophysical Society of America has appointed the undersigned as a committee upon comets.

It is the purpose of this committee to canvass the whole field of cometary research, inquiring what parts of that field will best repay systematic cultivation at the present time and securing, so far as possible, co-operation in such research. You are respectfully invited to communicate to any member of the committee suggestions with respect either to the subject-matter or the methods of such research or such other matter as may seem of advantage in this connection.

Very respectfully,

George C. Comstock, *Chairman*
Edward E. Barnard
Charles D. Perrine
Edward C. Pickering

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